DEVELOPMENT OF POLYCHROMATIC LASER BEACON FIBER COUPLING SYSTEM BASED ON PHOTONIC CRYSTAL FIBERS

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By
Ramyaa Ramesh Sangam, B.E.

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DEVELOPMENT OF POLYCHROMATIC LASER BEACON FIBER COUPLING SYSTEM BASED ON PHOTONIC CRYSTAL FIBERS

Name: Sangam, Ramyaa Ramesh

APPROVED BY:

Mikhail A. Vorontsov, Ph.D., D.Sc.  
Advisory Committee Chairman  
Professor & Wright Brothers Endowed Chair  
Electro-Optics Program

Thomas Weyrauch, Ph.D.  
Committee Member  
Senior Researcher  
Electro-Optics Program

Monish Chatterjee, Ph.D.  
Committee Member  
Professor  
Electrical & Computer Engineering

John G. Weber, Ph.D.  
Associate Dean  
School of Engineering

Tony E. Saliba, Ph.D.  
Dean, School of Engineering  
& Wilke Distinguished Professor
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ABSTRACT

DEVELOPMENT OF POLYCHROMATIC LASER BEACON FIBER COUPLING SYSTEM BASED ON PHOTONIC CRYSTAL FIBERS

Name: Sangam, Ramyaa Ramesh
University of Dayton

Advisor: Dr. Mikhail A. Vorontsov

The simultaneous characterization of laser beams of different wavelengths propagating through the atmosphere has been shown to be a valuable technique for the study of the effects of atmospheric turbulence and refraction on optical propagation. Previously, experiments were performed using three different single-mode fiber collimators with wavelengths 1.55 μm, 1.064 μm and 0.532 μm as laser beacons. The use of different (spatially separated) fiber collimators introduces uncertainties in the experiments such as the mutual pointing errors between the beacons. The goal of this thesis was therefore to implement a polychromatic laser beacon that transmits the three wavelengths mentioned above out of the same fiber collimator. A key requirement was to transmit only a single transverse mode (the fundamental mode of the fiber) for each wavelength. This was achieved using an “endlessly single-mode” photonic crystal fiber. To couple the light from three fiber lasers with different wavelengths and correspondingly different single-mode fibers into the photonic crystal fiber, a free-space
fiber coupling system using commercial off-the-shelf lenses was designed and optimized for best possible fiber coupling efficiency using ray-tracing software (Zemax). A tolerance analysis was performed to determine the sensitivity of the system to misalignments such as lens tilts, defocus and decenter. The analysis showed that realization of the fiber-coupling system was feasible considering typical manufacturing tolerances and precision of alignment. A prototype of the fiber coupling system based on the optical design was set up in the laboratory. In order to position the fiber tips accurately with sub-micrometer precision, fiber positioners based on piezo-electric actuators, which allow for electronically controlled lateral movement of the focused beam relative to the tip of the photonic crystal fiber, were employed in the fiber collimators. The experimentally observed fiber coupling efficiencies for the three wavelengths were in reasonably good agreement with values calculated with the Zemax ray tracing software. A secondary goal of the thesis was to demonstrate feedback control of the fiber coupling system for all three wavelengths simultaneously. Three parallel control loops were established using the fiber positioners along with commercially available controllers based on stochastic parallel gradient descent algorithm (SPGD) to ensure maximum coupling efficiency even under environmental disturbances such as mechanical stress, temperature changes and vibrations. Tests demonstrated the stability of the system with respect to large-amplitude vibrations at frequencies of several hertz. An off-axis parabolic mirror was used to set up a prototype of the polychromatic fiber collimator and components for feedback signal sensing were incorporated. The fiber coupling system and the fiber collimator were integrated for a laboratory demo of the fully working polychromatic beacon system.
I dedicate this work to my parents, grandparents, family and friends for their constant support, encouragement and wisdom.
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CHAPTER 1
INTRODUCTION

Atmospheric turbulence and refraction affect, and often ultimately limit, the performance of optical systems. The atmospheric impact is especially severe in near-horizontal near-ground and long-range optical propagation paths. To facilitate the development of optical systems for these scenarios, detailed knowledge and hence study of atmospheric effects is necessary. Recently, laser beam propagation experiments were performed for this purpose over a long propagation path of 149.2 km between two mountains, Mauna Loa (Hawaii) and Haleakala (Island of Maui), as part of the COMBAT (Coherent Multi-Beam Atmospheric Transceiver) experiments, and later over 7 km at the University of Dayton [1] [2]. These experiments are distinguished from similar trials, because they studied the effect of atmospheric turbulence on laser beam propagation simultaneously with three laser sources (beacons) of three different wavelengths, 1.55, 1.064 and 0.532 µm. Each of these wavelengths represents a spectral region of special interest: 1.55 µm lies in the window that has the lowest atmospheric attenuation and is therefore attractive for laser communication, 1.064 µm is a wavelength frequently used in high-energy laser applications, and the wavelength 0.532 µm represents the visible range, which is important for imaging applications.
The laser beacon assembly used in the COMBAT experiments consisted of three separate single-mode fiber collimators with their corresponding lasers. Each fiber collimator was equipped with means for manual alignment of the horizontal, vertical and axial position of the fiber tip with respect to the collimating lens for beam pointing and focus. In addition, piezoelectric fiber positioners that allowed for control of the lateral fiber-tip position in the collimators were used for fine beam steering. On the receiver side three different platforms, one each for each wavelength, were equipped with imaging systems that recorded the irradiance distributions in both the receiver telescope’s pupil plane and focal plane separately, but simultaneously, for each wavelength (Figure 1). These measurements allowed for determining characteristics of the beams after atmospheric propagation such as the magnitude of intensity fluctuations (scintillations) and angle-of-arrival fluctuations.

![Notional schematic of the polychromatic atmospheric propagation experiment with the three wavelengths 1.55 µm (λ₁), 1.064 µm (λ₂), and 0.532 µm (λ₃) propagating over a distance of 149 km (COMBAT experiments) or 7 km (at the UD test path). The receiver platform consists of the receiver telescope and imaging sensors that record pupil plane and focal plane irradiance distributions.](image)

There were certain issues with the beacon assembly (Figure 2) used in these experiments. In short range experiments, a mutual misalignment of beam directions between the collimators may cause in a considerable offset between the beam footprints at the receiver, resulting, for instance, in inconclusive results for determining the level of scintillation, which depends on the receiver aperture position relative to the beam
footprint. Moreover, the beams do not encounter the same refractive index fluctuations while propagating through the atmosphere, because the spatial separation of the beacons causes different paths for different wavelengths.

Figure 2: Three wavelength fiber collimated laser sources (where $\lambda_1=1.55\mu m$, $\lambda_2=1.064\mu m$, $\lambda_3=0.532\mu m$) are mounted on a gimbal. This beacon assembly was used in the COMBAT experiments over a 149 km propagation path as well as in experiments performed at UD over 7 km. The aperture of each collimator is 26 mm.

Over long propagation paths, the trajectories of the different wavelength beams begin to deviate due to the natural gradient of the refractive index of the air in the atmosphere. Because the index of refraction of air varies with wavelength, beams with different wavelengths experience different refraction. This causes a separation of beams of different wavelengths even if they are perfectly co-aligned at the transmitter side. In case of the 149 km propagation path, the separation between the beams with wavelengths 0.532 $\mu$m and 1.064 $\mu$m was estimated to be in the order of 4-5 m, roughly the diameter of the beam footprint [3]. Refraction can thus play an important role in long-range optical propagation and means for measurement and evaluation are desirable. If perfectly co-aligned beacons are available, the measurement of beam centroid separation for different wavelengths could be used as a tool.
The objective of this thesis was thus the development of a polychromatic laser beacon, which projects beams with the above mentioned three wavelengths from the same aperture and which ensures that the projected beams are highly parallel at the transmitter aperture. Such beacon can be realized as a fiber collimator, where all three wavelengths are launched through the same fiber. A key requirement was to transmit for each wavelength just a single transverse mode (the fiber’s fundamental mode) out of the collimator in order to avoid confusion of mode interference with irradiance fluctuations caused by atmospheric turbulence. Realization of such a collimator with conventional single mode fibers is not possible. As discussed in Chapter 2, Section 2.1. the operational wavelength range of conventional single-mode fibers is narrower than the desired range from 0.532 to 1.55 µm. A much wider wavelength range with single-mode operation is available with fibers based on photonic crystal technology. So-called “endlessly single mode” photonic crystal fibers (ESM-PCF) that remain single mode for a wide range of wavelengths (in some cases from 0.4 µm to beyond 2.0 µm) are commercially available. Basic properties of photonic crystals and specifications of the chosen ESM-PCF are discussed in Chapter 2, Section 2.2.

With a solution for the launch fiber found, the problem was how to simultaneously couple the light from very different wavelengths into the ESM-PCF. Although research and development has resulted in some promising approaches for fused photonic crystal couplers (Section 2.2.4), no suitable coupler has been commercially available. Consequently, there was a need to develop a free space fiber coupler that launches the discussed three wavelengths into the photonic crystal fiber. Its optical design with the ray-tracing software Zemax, the analysis of alignment tolerances, the setup of a
laboratory prototype system and its evaluation are a major part of this thesis. This included also the realization of adaptive fiber coupling using piezoelectric fiber actuators to optimally position the transmitting fiber tips by controllers implementing a stochastic parallel gradient descent algorithm (SPGD) to ensure maximum coupling efficiency, even under environmental distortions such as mechanical stress, temperature changes and vibrations. The implementation of three feedback loops (one per wavelength) working simultaneously was one of the secondary goals of this thesis.

Through optical design in Zemax it was shown that realization of the polychromatic beacon collimator with an apochromatic lens is possible. Due to the specific requirements – nearly identical focal length and good wave front quality at the three specified wavelengths – a custom lens would be necessary. In the prototype of the polychromatic beacon collimator that was set up for demonstration of the system an off-axis parabolic mirror that was available in the laboratory was used instead. Measurements of the feedback signals for the adaptive fiber coupling were realized using light within the Gaussian tails of the beams within the collimator, which would otherwise be truncated.

The remainder of this thesis is organized as follows: Chapter 2 discusses background relevant for the polychromatic beacon, including single-mode and photonic crystal fibers, Gaussian beams, fiber coupling, and wave front tip/tilt control with fiber positioners. In Chapter 3 the optical designs of the fiber coupling system and the beacon collimator are described along with a tolerance analyses. Chapter 4 describes the laboratory prototype of the polychromatic beacon and fiber coupling system and its evaluation. Chapter 5 discusses the realization and evaluation of the multi-wavelength
adaptive fiber coupling using piezoelectric fiber positioners. Preliminary experiments with the integrated beacon setup are described in Chapter 6.
CHAPTER 2
BACKGROUND

In this chapter the fundamental background for realization of the polychromatic beacon system is presented. This includes basic properties of single-mode fibers (Section 2.1) and photonic crystal fibers (Section 2.2), and Gaussian beam propagation (Section 2.3). In Section 2.4 the calculation of fiber coupling efficiency in general and for fiber-to-fiber coupling over free space is discussed. Wave front tip/tilt control in fiber collimators with piezoelectric fiber positioners is discussed in Section 2.5.

2.1 Single-mode Fibers

A conventional step-index fiber consists of a core with radius \( a \) with a refractive index \( n_{\text{core}} \) and a cladding with slightly lower refractive index \( n_{\text{cladding}} \), with,

\[
 n_{\text{cladding}} = n_{\text{core}}(1 - \Delta). \tag{1}
\]

For single-mode fibers the core cladding index difference \( \Delta \) is chosen anywhere between 0.2 to 1.0 % [4]. The solutions to the wave equation for the regions inside and outside the core are modes that are described by Bessel functions of the first order and modified Bessel function of the second order [4]. The cut-off wavelength separates the
spectral region, where a given fiber is considered single mode, from the multi-mode
region, where also higher order modes (beginning with LP$_{11}$) are guided.

The primary factor that determines the cut-off condition is the normalized
frequency $V$ (also called the $V$ parameter), which for conventional step index fibers is
given by

$$V = \frac{2\pi a}{\lambda} \left( n_{\text{core}}^2 - n_{\text{cladding}}^2 \right)^{1/2} = \frac{2\pi a}{\lambda} NA$$

(2)

Where $NA$ is the numerical aperture of the fiber and $\lambda$ is the wavelength in free space. $V$
is a dimensionless number that determines how many modes a fiber can support. If the $V$-
number is less than 2.405 only the mode with the lowest order Bessel functions is a valid
solution to the wave equation and only one mode, usually denoted as the LP$_{01}$ mode,
propagates. If the number becomes greater than 2.405, more modes are supported by the
fiber (starting with the mode LP$_{11}$ as shown in Figure 3) and the fiber is no longer single
mode.

![Figure 3: Pictures of the irradiance distributions of the fundamental (a) and higher order mode (b), LP$_{01}$
and LP$_{11}$ respectively [6].](image)

From this condition one can find the theoretical cut-off wavelength, $\lambda_{c}$, above
which single-mode operation occurs, and which is given by

8
Most single-mode fibers have \( V \) numbers close to the threshold of 2.405 for their design wavelength. In this case the light is confined mostly to the core and the wave guiding is less sensitive to distortions (especially to fiber bending) than for wavelengths much greater than the cutoff wavelengths. Bending losses as well as refractive index dispersion of core and cladding that changes the value of \( \Delta \) considerably limit the wavelength range in which use of a single-mode fiber at wavelengths well above \( \lambda_c \) is possible. Therefore single mode fibers have in general a limited range of useable wavelengths.

A survey of manufacturer specifications of commercially available single-mode fibers confirmed that there is no conventional single-mode fiber available that is suited for all three beacon wavelengths. A comparison of some properties of selected single-mode fibers from the Thorlabs catalog is shown in Table 1. It indicates that it is possible to achieve single-mode behavior simultaneously for 1.064 \( \mu \)m and 1.55 \( \mu \)m for example with the fiber 1060XP, but 0.532 \( \mu \)m is below its cut-off wavelength. Single-mode fibers designed for a shorter wavelength in the visible region are not useable at the two longer wavelengths in the near infrared.

\[
\lambda_c = \frac{2\pi a}{2.405} \left( n_{\text{core}}^2 - n_{\text{cladding}}^2 \right)^{1/2}
\]

1 This fundamental mode can consist of two orthogonal polarization states, which are referred to as "polarization modes". A single-mode fiber allows thus actually for propagation of two polarization modes with identical spatial intensity distribution.
Table 1: Comparison of some of properties of commercially available single-mode fibers.

<table>
<thead>
<tr>
<th>Fiber Type / Manufacturer</th>
<th>Specified Operating Wavelength Range (µm)</th>
<th>Specified Cut-off Wavelength (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>460HP</td>
<td>0.45-0.6</td>
<td>0.430±0.20</td>
</tr>
<tr>
<td>S630-HP</td>
<td>0.63-0.86</td>
<td>0.59±0.3</td>
</tr>
<tr>
<td>1060XP</td>
<td>0.98/1.064/1.55</td>
<td>0.92±0.3</td>
</tr>
<tr>
<td>SMF-28-J9</td>
<td>1.26-1.62</td>
<td>&lt;1.26</td>
</tr>
</tbody>
</table>

For single-mode fibers the fundamental mode’s spatial field distribution is usually approximated by a Gaussian distribution [4] as shown in Figure 4. This approximation is used throughout this thesis. The most important parameter characterizing the beam emerging from a single-mode fiber is the mode-field diameter, usually denoted as $MFD$. It is a function of optical source wavelength, the core radius and the refractive index profile of the fiber. The MFD is defined as the diameter where the power density is at 13.53% ($1/e^2$) of the maximum value.
Figure 4: A Gaussian beam distribution with the mode field diameter defined at the $1/e^2$ level of the maximum power density of the fundamental mode $LP_{01}$ is shown.

### 2.2 Photonic Crystal Fibers

Photonic crystals are periodic dielectric structures that have a band-gap that forbids propagation of a certain frequency range of light [7]. Wavelengths that are allowed to propagate are called modes and groups of these allowed modes are called bands. With this property (and specific super structures), one can control light and produce effects that are impossible with conventional optics.

Based on these properties two-dimensional photonic crystals have found commercial use in the form of Photonic-Crystal Fibers (PCFs). These fibers were first demonstrated by Russell [8]. They are made of pure silica-glass that contains multiple cylindrical air holes parallel to, and along the length of its axis. The holes are arranged in a regular periodic pattern and the core is defined by a defect such as a missing hole or a hole of a different size. The spacing between the hole centers is called the pitch, denoted
as \( \Lambda \), usually in the range of 1-10\( \mu \)m. PCFs guide optical waves via one of two mechanisms; effective-index guidance and photonic band-gap guidance [5].

2.2.1 Fibers with Photonic Band-gap Guidance

In optical fibers of this type a photonic band-gap effect is used to confine light to a waveguide. The first ‘photonic band-gap fiber’ also called ‘Bragg fibers’ was proposed by Yeh and Yariv in 1978 [9]. The first hollow core photonic band-gap fibers were demonstrated in 1999 by T.A. Birks et al., R.F. Cregan et al., [10]. Light of certain optical frequencies cannot propagate within the cladding structure, which is based on a two-dimensional photonic crystal. A defect, such as a missing hole, is introduced in the band-gap cladding to form the core and therefore light is confined to the core and not allowed to escape into the cladding. These fibers do not need a high refractive index core thereby allowing light propagation even within a hollow core (Figure 5). Such air-guiding hollow core PCFs can have a low non-linearity and are thus useful for high power applications. However, photonic-band-gap PCFs guide light in a narrow wavelength region with a typical width of 100-200 nm [4]. Therefore photonic band-gap guidance is not suitable for the application in the polychromatic beacon that covers a range of wavelengths from 532 nm to 1550 nm.
2.2.2 **Effective-index Guidance**

Effective-index guiding PCFs confine light by means of a modified total internal reflection mechanism. The core of the fiber is built of solid glass with refractive index $n_{core}$, whereas the cladding is in the form of a 2-dimensional photonic crystal structure, where an array of holes (typically in a hexagonal arrangement as shown in Figure 6) cause a reduction of the effective refractive index. If the hole diameter is much smaller than the wavelength of light ($d \ll \lambda$), then the periodic cladding behaves approximately as a homogenous medium whose effective refractive index $n_{eff}$ is equal to the average refractive index of the holey material [5]. If the hole size is comparable to the wavelength, then the cladding must be treated as a two-dimensional periodic medium and $n_{eff}$ becomes strongly dependent on the wavelength.

It was shown that the effective refractive index of the cladding $n_2(\lambda)$ is a decreasing function of wavelength [5] so that
This counteracts the dependence of the effective $V$ parameter on the wavelength $\lambda$,  

$$\sqrt{n_{\text{core}}^2 - n_{\text{eff}}^2(\lambda)} \propto \lambda$$  

(4)

$V_{\text{eff}} = \frac{2\pi A}{\lambda} \sqrt{n_{\text{core}}^2 - n_{\text{eff}}^2(\lambda)}$  

(5)

($A$ is the hole pitch), which thus becomes approximately independent of the wavelength and so extends the single-mode range [12]. Some PCFs may have the ability to operate over a wide range of wavelengths stretching from the infrared to the ultraviolet (300 to 2000 nm) [4]. This property is called endless single-mode (ESM) guidance. The values of the hole diameter and pitch are important to determine the characteristics of the fiber [5]. A diameter to pitch ratio of about $d/\Lambda < 0.43$ is needed for single-mode characteristics over a wide range of wavelengths [4]. Note that as a consequence of the wavelength dependence of the effective cladding index, the field becomes more concentrated in the medium of higher refractive index (the core) for shorter wavelengths.
Effective index guiding is, for instance, used to generate single-mode large-mode-area fibers, which are generally useful for high power applications to reduce the power density of guided modes. The guided mode size can be increased by having a larger pitch spacing (larger core diameter) and using holes with a smaller $d$ (lower numerical aperture) allowing the field to penetrate farther into the cladding [5].

2.2.3 ESM-PCF Fiber for the Polychromatic Beacon

Endlessly single-mode photonic crystal fibers (ESM-PCFs) are commercially available. For the polychromatic beacon project the fiber ESM-12B manufactured by NKT Photonics and distributed by Thorlabs, Inc. was available. It covers the desired wavelength range from 532 nm to 1550 nm. The key parameters of this fiber are summarized in Table 2.
Table 2: Properties of the endlessly single-mode photonic crystal fiber ESM-12B (from Thorlabs catalog).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode field diameter</td>
<td>10±1 µm</td>
</tr>
<tr>
<td>Core diameter</td>
<td>12.0 µm</td>
</tr>
<tr>
<td>Diameter of the holey region</td>
<td>60 µm</td>
</tr>
<tr>
<td>Cladding diameter (pure silica)</td>
<td>125±1 µm</td>
</tr>
<tr>
<td>Coating diameter (acrylate)</td>
<td>240±15 µm</td>
</tr>
<tr>
<td>Pitch Λ (spacing between the holes)</td>
<td>8.0 µm</td>
</tr>
<tr>
<td>Normalized hole diameter ( d / \Lambda )</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Figure 11 shows the near-field irradiance distribution of the ESM-12-01 fiber as provided by the distributor (Thorlabs) on a logarithmic irradiance scale. It is clearly visible that optical field has a hexagonal structure. However, a 90% overlap with the rotationally symmetric irradiance distribution of a Gaussian beam (see Section 2.3) is claimed by the manufacturer. The mode field diameter is supposed to be approximately independent of the wavelength. No data for the deviation were provided for the ESM-12-01 fiber. This fiber type was superseded by the fiber ESM-12B with nominally identical design parameters. Recent data sheets show a linear dependence of the MFD on the wavelength with an increase from about 10.0 µm to 10.6 µm for wavelengths from 0.7 µm to 1.7 µm.
2.2.4 Fused Fiber Couplers for PCFs

Fiber-based couplers between PCFs (fused couplers) are currently not commercially available. However, some publications can be found regarding research on such couplers over the last decade. A fiber coupler was initially developed with a photonic crystal fiber using the fused biconical tapering (FBT) method operating at a wavelength of 1550 nm. [13] Recently, photonic crystal fiber couplers (PCFC) operating over a wider range of wavelength (such as 900 to 1700 nm and 500 to 1400 nm) have been developed. [14] [15] However these PCFC’s do not cover the wide and specific wavelength range from 0.532, to 1.55 µm. In addition, the coupling efficiency for shorter wavelengths is rather poor.

2.3 Gaussian Beam Optics

Gaussian beams are solutions of the paraxial Helmholtz equation with a Gaussian intensity profile. The complex amplitude of a Gaussian beam propagating along the z axis can be expressed as  [16]
\[ E(r, z) = E_0 \frac{w_0}{w(z)} \exp \left( -\frac{r^2}{w^2(z)} \right) \exp \left[ -j \left( k z + \frac{kr^2}{2R(z)} - \zeta(z) \right) \right], \quad (6) \]

where \( r \) is the radial distance from the beam center, \( k = 2\pi/\lambda \) is the wave number, and \( j^2 = -1 \). \( w(z) \) is the radius at which the amplitude drops to \( 1/e \) of the on-axis value (equivalent to the intensity dropping to \( 1/e^2 \) of its axial value) and is given by

\[ w(z) = w_0 \sqrt{1 + \left( \frac{z}{Z_R} \right)^2}, \quad (7) \]

if the beam waist (with the smallest beam radius along the \( z \) axis) is assumed to be at \( z = 0 \). The wavefront radius of curvature can then be described as

\[ R(z) = z \left[ 1 + \left( \frac{Z_R}{z} \right)^2 \right]. \quad (8) \]

The Gouy phase shift

\[ \zeta(z) = \arctan \left( \frac{z}{Z_R} \right), \quad (9) \]

is an additional contribution to the phase that is mostly relevant near the beam waist.

\[ Z_R = \frac{kw_0^2}{2} = \frac{\pi w_0^2}{\lambda} \quad (10) \]

is called the Rayleigh range. At a distance \( Z_R \) from the waist, the beam cross sectional area is double the area at the waist and the radius \( w(Z_R) = \sqrt{2}w_0 \). The wavefront radius of curvature is the smallest for \( z = Z_R \).
For $z \gg z_R$ one can approximate Equation (7) by

$$w(z) \approx w_0 \frac{z}{z_R}.$$  \hspace{1cm} (11)

Therefore, the beam radius grows approximately linearly with $z$ for distances from the beam waist large in comparison to the Rayleigh range. From (11) we can derive the expression for the (half) angle of divergence $\theta$ defined through $\tan \theta = \lim_{z \to \infty} w(z)/z$ as

$$\theta = \arctan \left( \frac{W_0}{Z_R} \right) = \arctan \left( \frac{\lambda}{\pi W_0} \right).$$  \hspace{1cm} (12)

The wavefront radius of curvature (8) can be approximated for $z \gg z_R$ as

$$R(z) \approx z.$$  \hspace{1cm} (13)

An ideal (infinitely thin) lens with focal length $f$ placed in the path of the Gaussian beam generates a new Gaussian beam after passing the lens. At the lens location the refracted beam has the same radius as the incident beam. The wavefront radius of curvature $R_{refr}$ after the lens is given by

$$\frac{1}{R_{refr}} = \frac{1}{R_{inc}} - \frac{1}{f},$$  \hspace{1cm} (14)

where $R_{inc}$ is the wavefront radius of curvature of the incident beam [17]. Therefore, a Gaussian beam with its waist located at the front focal plane of a positive lens ($R_{inc} = f$) is transformed into a Gaussian beam that has an infinite radius of curvature at the lens. This means the beam waist of the refracted beam, which must have a larger radius than
the waist of the incident beam, is located at the lens as long as the approximation for the far field given in Equation (13) can be applied.

2.4 Calculation of Fiber Coupling Efficiencies

Efficient fiber coupling of an optical beam typically requires focusing of the beam onto the tip of the fiber and a match between the phase and amplitude of the field of the focused beam and the fiber mode field. The coupling efficiency \( \eta \) is calculated using the known overlap integral [18] which is given by

\[
\eta = \frac{\left| \int_{-\infty}^{\infty} E_{\text{focus}} E_{01}^* dA \right|^2}{\int_{-\infty}^{\infty} |E_{\text{focus}}|^2 dA \int_{-\infty}^{\infty} |E_{01}|^2 dA}
\]

where \( E_{\text{focus}} \) is the field of the focused beam at the fiber tip, \( E_{01}^* \) is the field of the (fundamental) guided mode of the fiber, * denotes a complex conjugate, and integration is performed over the (infinite) plane that contains the fiber tip (see Figure 8). Assuming a Gaussian beam, uniform phase requirement means the beam waist must be at the fiber tip and the beam waist diameter must match the mode field diameter of the fiber.
Figure 8: Coupling of light into a single-mode fiber. Uniform phase requirement means the beam waist must be at the fiber tip and the beam waist diameter must match the mode field diameter of the fiber. $E_{01}$ is the field of the (fundamental) guided mode of the fiber. $E_{\text{focus}}$ is the field of the focused beam at the fiber tip. $2\theta$ indicates the beam divergence and MFD is the fiber’s mode field diameter.

For Gaussian beams and Gaussian mode field distribution, one can calculate fiber coupling efficiencies for beam radius mismatch and lateral displacement of the beam using the equation

$$
\eta = \frac{4w_{01}^2w_{\text{focus}}^2}{(w_{01}^2 + w_{\text{focus}}^2)^2} \exp \left[ -\frac{2(\Delta r)^2}{w_{01}^2 + w_{\text{focus}}^2} \right],
$$

(16)

where $w_{01}$ is the mode field radius ($2w_{01} = MFD$), $w_{\text{focus}}$ is the radius of the beam at the fiber tip, and $\Delta r$ is the lateral displacement between mode field and focused beam [19].

If the lateral displacement $\Delta r = 0$, then the argument of the exponential function (second term in Eq. 16) becomes zero and we can use the first term to calculate the fiber coupling efficiency for a size-mismatched focused beam that is ideally centered on the fiber core. The result in Figure 9 shows that the coupling efficiency is not very sensitive
to a size mismatch. A variation of the beam diameter between 90% and 110% of the mode field diameter has a negligible impact on the coupling efficiency and even larger deviations from the ideal beam size can be tolerated with little penalty.

Figure 9: Fiber coupling efficiency for a mismatch between the radius of the focused beam, $w_{focus}$ and the mode field radius $w_{01}$.

Figure 10: Fiber coupling efficiency for the real defocus of the beam with respect to the optimal position considering size and phase.
The plot in Figure 10 shows that defocusing the beam by 100 µm results in a 50% reduction of the coupling efficiency. This indicates that beam defocus is not as critical as compared to lateral displacement of the focused beam.

The situation is different if we evaluate the coupling efficiency in Eq. 16 for the dependence on the lateral displacement (assuming ideal field diameter). The graph in Figure 11 shows that displacing the beam by half of the mode field radius results in a 50% reduction of the fiber coupling efficiency. Exact lateral positioning of the focused beam onto the fiber tip is thus very important.

Figure 11: Fiber coupling efficiency in dependence on the lateral displacement of the field of the focused beam with respect to the optimal position. The lateral displacement \( \delta r \) is normalized to the mode field radius \( w \). An optimal beam size \( w_{\text{focus}} = w_{01} = w \) is assumed.

For angular misalignments, the following expression can be used for the fiber coupling efficiency [18]:

\[ \text{Coupling Efficiency} = 100 \left(1 - \frac{\delta r}{w}\right) \]
\[ \eta = \exp \left[ -\left( \frac{\pi (\Delta \alpha) w}{\lambda} \right)^2 \right], \]  

(17)

\( \Delta \alpha \) is the angular mismatch between mode field and focused beam. Here we assume that the radii are matched so that \( w = w_{01} = w_{f \text{ocus}} \). This dependence is plotted in Figure 12 for a ratio of \( w/\lambda = 3.36 \) typical for single mode fibers. It shows that angular alignment should be performed with accuracy of 1.5° or better in order to keep the coupling efficiency above 90%. Such precision is not difficult to obtain during the alignment procedure as an angle of 0.5° can be recognized visually.

![Figure 12](image)

Figure 12: Fiber coupling efficiency calculated for angular misalignment between focused beam and fiber tip.

### 2.5 Wavefront Tip/Tilt Control with Fiber Positioners

From the plots we see that lateral displacement of the beam is most critical considering that mode field diameters are usually in the order of several micrometers.
Moving the beam laterally relative to the fiber even over a small distance of 0.6 \( \mu \text{m} \) reduces the coupling efficiency considerably. Environmental influences (mechanical stress, thermal expansion, platform jitter, etc.) can therefore reduce the coupling efficiency considerably.

Hence active fiber positioning with piezo-actuator were considered in the fiber coupling system. These fiber positioners move each transmitting single-mode fiber (but not the photonic crystal fiber) to laterally move each beam’s focal spot relative to the tip of the photonic crystal fiber. The fiber positioners used in the experimental setup are commercially available [part of the INFOCO (Intelligent Fiber-Optics Collimator) system from Optonicus]. Use of the fiber positioners and the INFOCO controllers, which use the SPGD algorithm discussed in Section 2.5.2, does not only allow for active optimization during operation of the coupling system, but also helps to reduce the alignment burden.

2.5.1 Piezoelectric Fiber Positioners

The design of the fiber positioner is based on four piezo-electric bimorph actuators, two that drive the X direction and two that drive the Y direction [20]. Figure 13 shows the basic parts of a fiber-positioner. Each actuator consists of piezo-electric sheets with electrodes arranged such that when a voltage is applied one part of the sheet expands and the other part contracts which results in bending. The important part of the X-Y positioner is the X-Y cross made of titanium that helps in the bending of the actuators. This cross helps couple the X and Y channels such that when voltage is applied to the electrodes, the X beams bend driving the Y channel and leads to deformation of the X channel actuators shown in Figure 13 (b).
The fiber, mounted within a tube in the center of the X-Y cross, is positioned by applying voltage within the range of ±70V. The frequency bandwidth of the used fiber-positioners is about 5 KHz. Together with a collimating lens, fiber positioners can be used to fine-adjust the direction of a collimated lens. For 1.55 µm, the focal length of the lens used is 100mm and the tip/tilt deviation of the collimated beam is in the range of 0.5 mrad from the optical axis. The X, Y displacement is then 50 µm. Similarly for 1.064 and 0.532 µm the focal length is about 75mm and 30.10mm respectively. Hence the fiber tip displacement is 37.5 µm and 15 µm respectively.

![Figure 13: Schematic of the basic parts of the fiber positioner with four piezo-electric bimorph actuators as shown in (a). When voltage is applied to the actuators the X beams bend driving the Y channel actuator and leads to deformation of the X channel actuator as shown in (b).](image)

2.5.2 Stochastic Parallel Gradient Descent (SPGD) Algorithm

The stochastic parallel gradient descent control technique has been used since the 1990’s in adaptive optics alongside other methods like multi-dithering as wavefront control technique.

SPGD is typically used in an optical system containing a wavefront corrector with $N$ actuators and a system performance metric sensor giving a signal that acts as a quality measure of the corrected wavefront. Small perturbations $\Delta a = \{\Delta a_j\}$ of the control signals $a = \{a_j\}$ are applied to all $N$ actuators. The perturbation values $\{\Delta a_j\}$ are so small that they result in a small change (variation) of the measured system performance
metric $J$. The INFOCO controller implements the following SPGD rule. Positive and negative perturbations are applied simultaneously (in parallel) to the control voltages [21]. The system’s performance response metric $J_\pm$ to the positive and negative perturbations is measured. The performance metric variation $\Delta J$ is calculated as the difference between the input voltages $J_+$ and $J_-$ measured for positive and negative perturbations respectively which can be written as [16],

$$\Delta J = J(a_1 + \Delta a_1, ..., a_j + \Delta a_j, ..., a_N + \Delta a_N) - J(a_1 - \Delta a_1, ..., a_j - \Delta a_j, ..., a_N - \Delta a_N)$$

(18)

Knowing the values of $\Delta J$ and by measuring the performance metric before and after application of the perturbations $\{\Delta a_j\}$, new control signal values for the actuators are calculated according to the update equation [16]:

$$a_j^{(n+1)} = a_j^n + \gamma_j^{(n)} \Delta J^{(n)} \Delta a_j^{(n)}, \quad j=1, ..., N, \quad n = 0, 1, 2, ...$$

(19)

where $a_j^n$, $\{\Delta J^{(n)}\}$, $\{\Delta a_j^{(n)}\}$, and $\{\gamma_j^{(n)}\}$ are the control signals, metric variation, control signal perturbations and update (gain) coefficients at the $n^{th}$ iteration, respectively. Figure 14 shows a timing diagram showing the parallel update of the control voltage and perturbations as well as time development of the perturbation metric for two iterations.
Figure 14: The timing diagram has been redrawn from the original [21][22]. The diagram for the control signals $a_j$ (top) and performance metric $J$ (bottom) in the SPGD iterative process with sequentially updated controls and perturbations (positive and negative) are shown. The metric measurement time is shown in small circle ($o$) and $J_j^{(n)}$ corresponds to the metric value resulting from applied perturbation at the $n^{th}$ iteration. The applied control values are shown by solid horizontal lines.

The convergence rate in this method is significantly faster than single-sided perturbations [16]. The time for one iteration $\tau_{it}$ is given by $\tau_{it} = 2\tau_c$ where $\tau_c$ is the control system response time. The convergence time is given as,

$$\tau_{conv}^{SPGD} = 2n_{conv}\tau_c$$  \hspace{1cm} (20)
Where \( n_{\text{conv}} \) is the convergence rate or the number of iterations required for the metric optimization process convergence. The convergence rate also depends on other factors such as gain coefficients \( \gamma_f^{(n)} \) and perturbation characteristics, gradient estimation accuracy, noise level in metric measurements, aberrations etc. The control system response time \( \tau_c \) from Equation (20) is defined by the time response or operational bandwidth of the wave front correctors (bimorph actuators).
In this chapter the optical design of both the fiber coupling system and the beacon collimator is presented. In Section 3.1 the basic principles for coupling light from a source fiber into a receiving fiber in free-space with two lenses are discussed and extended for three wavelengths with individual source fibers. The optimization method and underlying system parameters for optical design with the ray tracing software Zemax are briefly described in Section 3.2. Section 3.3 discusses the strategy involved in choosing off-the shelf lenses and beam splitters for the fiber coupling system and presents the chosen optical design. A tolerance analysis, performed to determine the sensitivity of the system to misalignments, is described in detail in Section 3.4. Other alternative optical designs that were briefly considered are discussed in Section 3.5. Design and analysis of an apochromatic lens as possible solution for collimation of the diverging beams emerging from the photonic crystal fiber are discussed in Section 3.6.
3.1 Free-space Fiber-to-fiber Coupling with a Two-lens System

To couple light from a source fiber into a receiving fiber, one has to image the Gaussian beam waist at the source fiber onto the tip of the receiving fiber with the correct magnification. In order to do this efficiently for three different single-mode source fibers (at different wavelengths), one must consider that the in general different source beam waist diameters \(2w_A^{SMF}\) require different imaging systems to match the mode field diameter at the receiving fiber, which is assumed to be a PCF with wavelength-independent mode field diameter \(2w_{P_{CF}}\). A potential solution is the use of two lenses (a collimating lens, \(L_1\), at the source fiber and a focusing lens, \(L_2\), at the PCF) and a nearly collimated beam between the lenses as shown in Figure 15. In this approach, the beams are combined while (nearly) collimated (between \(L_1\) and \(L_2\)) and lens \(L_2\) will be used for all three wavelengths. Since the beam waist radius at the source \((w_A^{SMF})\) is dependent on the wavelength, different lenses \(L_1\) need to be used and the focal lengths \(F_A\) and \(F_{P_{CF}}\) of the collimating lenses and the focusing lens, respectively, need to be selected in such a way that the correct beam waist radius at the photonic crystal fiber is obtained for all wavelengths.

![Figure 15: Two-lens fiber-to-fiber coupling schematic showing a 1:1 imaging of the Gaussian beam waist at the source fiber \((w_A^{SMF})\) onto the tip of the PCF \((w_{P_{CF}})\) with lenses \(L_1\) and \(L_2\) and their respective focal lengths \(F_A\) and \(F_{P_{CF}}\).](image)
In order to determine an estimate of the focal lengths $F_{\lambda}$ in dependence on the waist radii $w_{\lambda}$ and $w_{PCF}$ as well as on the focal length of the focusing lens $F_{PCF}$ we use the properties of a Gaussian beam emerging from the single mode fiber. With the wavelength in the order of one micrometer and the beam waist radius at the fiber in the order of a few to about 5 $\mu$m, the Rayleigh range $z_R = \pi w_0^2 / \lambda$ is less than 0.1 mm for all fibers. We can thus assume $z \gg z_R$ and use Equations (10) and (11) to approximate the beam radius by the expression

$$w(z) \approx \frac{z \lambda}{\pi w_{\lambda}}, \quad (21)$$

where $z$ is the distance from the fiber tip and $w_{\lambda}$ is the mode field radius. A lens with focal length $F_{\lambda}$ at a distance $z = F_{\lambda}$ from the source fiber (the fiber tip is located in the focal plane) creates therefore (in thin-lens approximation) a Gaussian beam of radius

$$w_{\lambda,\text{coll}} \approx \frac{F_{\lambda} \lambda}{\pi w_{\lambda}} \quad (22)$$

with a new beam waist at the lens. We can use the same derivation to determine the collimated beam radius that is necessary to generate a beam radius of $w_{PCF}$ on the photonic crystal fiber’s tip in the focal plane of the focusing lens with focal length $F_{PCF}$:

$$w_{\lambda,\text{coll}} \approx \frac{F_{PCF} \lambda}{\pi w_{PCF}} \quad (23)$$

Combining Equations (22) and (23), we find the necessary focal length $F_{\lambda}$ for lens $L_1$ to achieve good fiber coupling for a given wavelength $\lambda$ and focal length of the focusing lens $F_{PCF}$:
The focal length of the collimating lens must thus be proportional to the beam waist radius \( w_\lambda \) of the beam emerging from the single-mode fiber and hence proportional to the fiber’s mode field diameter \( MFD = 2w_\lambda \). Note that the angle of divergence [Equation (12)] of the beam emerging from conventional single-mode fibers is nearly independent of the wavelength, because \( MFD \) is approximately proportional to the wavelength \( \lambda \). This means \( w_\lambda \propto \lambda \) and from Equation (24) follows that the focal length of the collimating lens needs to be proportional to \( \lambda \).

In order to size the diameter of both the collimating lens \( L_1 \) and the focusing lens \( L_2 \), we need not only consider the beam radius \( w_{\lambda,\text{coll}} \), but also a reasonable level at which to truncate the (in theory) infinite Gaussian beam. Typically clipping at the level of 1% of the maximum intensity is considered to be sufficient for letting Gaussian beams propagate nearly undistorted through apertures. This is approximately fulfilled, if the beam diameter \( d_{\lambda,\text{coll}} \) that can pass through the aperture is at least three times the Gaussian beam radius, i.e., \( d_{\lambda,\text{coll}} = 3w_{\lambda,\text{coll}} \). Consequently, we must tailor the beam diameter to be proportional to the waist radius at the fiber and thus proportionally to the wavelength.

From Equation (24), we know that at the photonic crystal fiber, the mode field radius \( w_{PCF} \) is independent of wavelength. To get good coupling conditions, the beam width at the focusing lens \( L_2 \) increases linearly with wavelength. Hence the size of the lens needs to be chosen such that the correct beam waist radius is obtained for all three
wavelengths. At the collimating side the beam waist radius $w_{1.55}$ for 1.55 µm is the largest because the wavelength is the largest. Therefore the focal length $F_{1.55}$ must also be the largest. For 1.064 µm and 0.532 µm, both the beam waist radii ($w_{1.064}$ and $w_{0.532}$) and the focal lengths ($F_{1.064}$ and $F_{0.532}$) are proportionally to the wavelength. Thus, three different collimating lenses $L_{1a}$, $L_{1b}$ and $L_{1c}$ were chosen such that their focal lengths are proportional to the corresponding wavelength. Based on these estimates, a principle schematic of the optical system for coupling these three beams of different wavelengths from different source fibers into a single photonic crystal fiber as shown in Figure 16 was developed. In order to combine the beams and focus them into the photonic crystal fiber, dichroic beam splitters $BS_1$ and $BS_2$ are chosen such that $BS_1$ transmits 1.55 µm and reflects 1.064 µm and $BS_2$ transmits both 1.55 and 1.064 µm and reflects 0.532 µm.

Figure 16: Schematic of a system for fiber-to-fiber coupling of three different wavelengths from three different conventional single-mode fibers into one photonic crystal fiber. $BS_1$ and $BS_2$ are cube beam splitters. Lenses $L_{1a}$, $L_{1b}$, $L_{1c}$ are collimating lenses that collimate the beams from the single-mode fiber (SMF) and focus it into the photonic crystal fiber (PCF) using the focusing lens $L_2$. $d_{1.55}, d_{1.064}$ and $d_{0.532}$ are Gaussian beam diameters for 1.55, 1.064 and 0.532 µm respectively. $d_1$ is the wavelength-specific Gaussian beam diameter at the photonic crystal fiber. $F_{1.55}, F_{1.064}$ and $F_{0.532}$ are the focal lengths of the collimating lenses $L_{1a}$, $L_{1b}$, $L_{1c}$. $F_{PCF}$ is the focal length of the focusing lens $L_2$ at the PCF. $w_{1.55}, w_{1.064}, w_{0.532}$ are the beam waist radius at the single-mode fiber for each of the wavelength. $w_{PCF}$ is the beam waist at the photonic crystal fiber which is wavelength independent and assumed to be constant.
3.2 Optical Design Optimization with the Ray Tracing Software Zemax

In the calculations above we made a number of approximations to calculate some basic system parameters. Among the assumptions were perfect collimation by ideal thin lenses with negligible thickness and without wavefront and chromatic aberrations. In order to design a system with real optical elements, the actual dimensions and aberrations need to be considered. We used the ray tracing software Zemax [23] as a tool for the design and analysis of a realistic (non-idealized) fiber coupling system. Zemax provides an optimization tool that can be used to optimize a lens design by automatically adjusting user-selected design parameters to maximize a user-defined merit function. For most optical systems, it is useful to define the merit function in terms of the residual wavefront aberration. For a fiber coupling system, however, it is preferable to optimize the fiber coupling efficiency, \( \eta \), as defined over the overlap integral [Equation (15)], because not only the wavefront aberrations need to be minimized but also the beam size needs to match the mode field size of the fiber. Optimizing only the wavefront may result in a too large mismatch of the field size. Zemax provides a tool for calculation of fiber coupling efficiencies in an approximation that mixes geometric and physical optics methods. Zemax’s fiber coupling efficiency can be used as a merit function for optimization. The calculation is performed as the product of the system and receiver efficiency using the Huygens integration method. The system efficiency is the fraction of the energy in the source beam that exits the optical system towards the receiver fiber. This is calculated using the input numerical aperture (of the source fiber), size and position of the entrance pupil and other factors. The receiver efficiency is calculated using the wavefront aberrations and the receiving fiber numerical aperture. Each fiber’s numerical aperture is
defined as \( NA = \sin \theta \) with the angle of divergence \( \theta \) as defined in Equation (12). In linear approximation we have thus for the source fibers

\[
\theta = \frac{\lambda}{\pi w_\lambda}
\]  

(25)

and for the receiving fiber (here the PCF)

\[
\theta = \frac{\lambda}{\pi w_{PCF}}.
\]  

(26)

\( 2w_\lambda \) and \( 2w_{PCF} \) correspond to the mode field diameters, \( MFD_\lambda \) and \( MFD_{PCF} \), of source and receiving (PCF) fibers, respectively. Note that while the receiver mode field diameter \( (MFD_{PCF} \) of the photonic crystal fiber) is assumed to be constant, the numerical aperture varies with the wavelength. The numerical aperture values used for the Zemax optical design were calculated from the specifications for the single-mode source fiber and the photonic crystal fiber. The values are listed in Table 3. Note that for the receiver (photonic crystal fiber) a value of \( MFD_{PCF} = 10.4 \mu m \) was used for all wavelengths.

Table 3. List of mode field diameters of the source fibers and numerical aperture values of the source fiber and receiver fiber (PCF) used for fiber coupling calculations with Zemax.

<table>
<thead>
<tr>
<th>Wavelength, ( \lambda ) (( \mu m ))</th>
<th>( MFD_\lambda ) (( \mu m ))</th>
<th>( NA_\lambda )</th>
<th>( NA_{PCF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>10.4</td>
<td>0.095</td>
<td>0.095</td>
</tr>
<tr>
<td>1.064</td>
<td>6.2</td>
<td>0.101</td>
<td>0.0657</td>
</tr>
<tr>
<td>0.532</td>
<td>3.5</td>
<td>0.0969</td>
<td>0.0329</td>
</tr>
</tbody>
</table>
3.3 Optical Design of the Fiber Coupling System

One goal of the optical design was to find a solution for the fiber coupling system with acceptable coupling efficiencies using only commercial off-the-shelf (COTS) lenses. A secondary goal was to keep the system as compact as possible, which means to keep focal lengths of collimating lenses and the focusing lens small. A major constraint was the intention to use commercial fiber positioning systems within the source collimators in order to be able to actively compensate for lateral fiber position errors (see Chapters 4 and 5). The fiber positioners need a minimum distance between fiber tip and lens of approximately 30 mm. Hence, the shortest focal length of any lens in the system must be not less than this value. As discussed above, the shortest focal length is needed for the collimating lens for $\lambda = 0.532 \mu m$, while the other focal lengths proportional to the wavelength are larger (i.e., about three times for the longest wavelength 1.55 $\mu m$). We were thus looking for lenses with a focal distance in the range from 90 to 100 mm for the focusing lens and the lens for collimation of the light at 1.55 $\mu m$, a focal distance in the range from 30 to 35 mm for the collimating lens at 0.532 $\mu m$, and within the range from 60 to 75 mm for collimating light at 1.064 $\mu m$. The required lens size is determined by the collimated beam diameter resulting in clipping of 1% of the energy of a Gaussian beam given by

$$d_\lambda = 3w_{\lambda, coll} \approx 3 \frac{F_{PCF}}{\pi} \frac{\lambda}{w_{PCF}}$$

(27)
which results in $d_\lambda = 28.3$ mm for the largest lens at $\lambda = 1.55 \, \mu m$. Since many lenses are available at about 1 inch diameter, we also took lenses of this slightly smaller diameter into consideration. The design strategy was then as follows:

1. Find a pair of identical COST lenses for efficient coupling from the source fiber into the PCF at 1.55 $\mu m$. Achromatic doublet lenses were the primary choice because they partially compensate spherical wavefront aberrations and are, in general, optimized for a finite/infinite conjugate ratio, as required for a collimating lens.

2. Fix the found distance between focusing lens and PCF and find COST achromatic lenses for collimating the light at 0.532 $\mu m$ and 1.064 $\mu m$; optimize coupling into the PCF by varying the distance between the source fiber and the collimating lens.

In both steps, basically all lens designs that were available in the Zemax database (lens catalog) and that had reasonable parameters were analyzed. A catalog of solutions that provided reasonably good spot sizes and wavefront aberrations, and, most importantly, good coupling efficiencies were elaborated and the overall best design configuration was determined. Then the availability of lenses and desired anti-reflection coatings was investigated with the vendors. In a second iteration, the best practicable solution with actually available lenses was selected. For the 1.55 $\mu m$ collimator and the focusing lens, achromats from JML Optics (DBL14020100) with a focal length of 100mm and a diameter of 25mm were chosen. For 1.064 $\mu m$ the best design was with a Thorlabs achromat (AC254-075-C) with a focal length of 75mm, diameter of 1 inch and for 0.532 $\mu m$ an achromat from Opto-Sigma (026-0180) with a focal length of 30.10mm and a diameter of 10mm performed best. The resulting final optical design is shown in
Figure 17. As can be seen from the figure, dichroic surfaces on optical windows (plate beam splitters) are used in the collimated beam path to combine the beams of different wavelengths. In comparison to cube beam splitters, the tilted glass substrate cause slightly larger aberrations and make alignment of the system more difficult because of lateral beam shifts. However, appropriate dichroic cube beam splitters are not available off the shelf. Hence dichroic plate beam splitters were finally decided upon. One of the important specifications was to have one beam splitter that transmitted 1.55 µm and reflected 1.064 µm and another beam splitter that transmitted 1.55, 1.064 µm and reflected 0.532 µm. Several beam splitters were considered from various vendors depending on their availability, price and the specifications. Two long-wave pass dichroic beam splitters from CVI Melles Griot (LWP-45-RUNP1064-TUNP1550-PW-2025-C, LWP-45-RUNP532-TUNP1064-PW-2025-C) were chosen with a diameter of 2 inches and a thickness of 0.25 inches. They are made of fused silica for an angle of incidence of 45 degrees. The average transmission of the beam splitters according to manufacturer’s specifications was greater than 85% and the reflection was greater than 99%. The peak to valley wave front was specified as $\lambda/10$ waves. The system schematic is shown in Figure 8.
Figure 17: Optical design of a fiber coupling system for coupling three beams of different wavelengths from different single-mode fibers into a single photonic crystal fiber. The design is based on commercially available lenses. Lens L_{1a} and Lens L_{2} are uncoated achromats chosen from JML optics (DBL14020100). Lens L_{1b} and L_{1c} are achromats selected from Thorlabs (AC254-075-C) and Opto-Sigma (026-0180) respectively. BS_{1} and BS_{2} are dichroic long wave pass beam splitters chosen from CVI Melles Griot (LWP-45-RUNP1064-TUNP1550-PW-2025-C and LWP-45-RUNP532-TUNP1064-PW-2025-C).

A summary of the optical design parameters with the calculated fiber coupling efficiencies, wave front aberrations, Strehl ratios, beam sizes, and mode field diameters of the single-mode and photonic crystal fibers is provided in Table 4 below. The most notable result is that the coupling efficiency calculated by Zemax is better than 90% for the two shorter wavelengths and still better than 80% for 1.55 µm, although the smaller-than-ideal lens size causes a penalty from higher beam truncation.
Table 4: Summary of the optical system design parameters for the three different beam paths. Quantities marked with an asterisk (*) were determined for an aperture size that contains 92% of the power. (Note that the coupling efficiency does not consider any losses through reflection at surfaces).

<table>
<thead>
<tr>
<th>Wave-length, $\lambda$ (µm)</th>
<th>1.55</th>
<th>1.064</th>
<th>0.532</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode field diameter (source), $2w_\lambda$ (µm)</td>
<td>10.4</td>
<td>6.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Beam size at PCF, $2w_{PCF}$ (µm)</td>
<td>10.4</td>
<td>10.34</td>
<td>11.68</td>
</tr>
<tr>
<td>Diameter of collimated beam, $d_\lambda$ (mm)</td>
<td>28.32 (unclipped)</td>
<td>19.57</td>
<td>8.66</td>
</tr>
<tr>
<td>Nominal focal length of lens $L_1$, $f_\lambda$ (mm)</td>
<td>100</td>
<td>75</td>
<td>30.1</td>
</tr>
<tr>
<td>Diameter of Lens $L_1$ (mm)</td>
<td>25</td>
<td>25.4</td>
<td>10</td>
</tr>
<tr>
<td>Coupling efficiency, calculated with Zemax, $\eta_{Zemax}$ (%)</td>
<td>82.8</td>
<td>95.1</td>
<td>93.5</td>
</tr>
<tr>
<td>Wave front error, peak-to-valley, (waves)*</td>
<td>0.2</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Strehl ratio*, $St$</td>
<td>0.89</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

The wavefront aberrations given in Table 4 were calculated over an area that contains 92% of the beams energy (an area with a diameter of $2.25w_\lambda$) and neglect thus an annular region with the Gaussian beam tails that do not contribute much to the fiber coupling efficiency. The wavefront aberrations calculated using Zemax over the whole exit pupil is shown in Figure 18. The peak-to-valley values are about $\lambda/3$ for 1.55 µm, $1.2\lambda$ for 1.064 µm, and $\lambda/9$ wave for 0.532 µm. The beam path for 1.064 µm has considerably larger aberrations than for the other two wavelengths. However, as can be seen from Figure 18, the major aberrations are in the annular zone next to the rim of the pupil and have only little impact onto the fiber coupling efficiency.
3.4 Tolerance Analysis of the Fiber Coupling System

The fiber coupling efficiencies reported above were calculated for an ideally aligned system. However, small variations in the alignment of optical elements may cause a significant loss in performance. In order to estimate the necessary precision of the
alignment, a tolerance analysis with respect to lens tilt, defocus, and decenter was performed. Misaligned systems were modeled with Zemax, which was also used to calculate the corresponding fiber coupling efficiencies.

3.4.1 Tolerance to Tilting of the Collimating Lens

In the Zemax model each of the collimating lenses for all the three wavelengths (1.55, 1.064 and 0.532 µm) was tilted until the peak-to-valley wavefront and the fiber coupling efficiency started to deviate considerably from the ideal alignment. In Figure 19, the fiber coupling efficiency as well as the peak-to-valley wavefront aberrations are plotted vs. the lens tilt angle for all three wavelengths. For 1.55 µm and 0.532 µm a lens tilt of 1 degree doesn’t cause a noteworthy reduction of the coupling efficiency (and has still acceptable efficiency at 1.5 degrees). Such tolerance is not difficult to meet in an opto-mechanical system. However, a tilt of the lens of the collimator for 1.064 µm causes significant performance reduction even for tilt angles of 0.2 degrees. Thus, the tilt angle of this collimating lens will be the most cumbersome to align.
Figure 19: Results from the tolerance analysis of the fiber coupling system. Plotted are the coupling efficiency (in %) and the peak-to-valley wavefront aberration (in waves) vs. the tilt angle (in degree) of the collimating lens shown in (a), (b), (c) for 1.55, 1.064 and 0.532 µm.
3.4.2 Tolerance to Tilting of the Focusing Lens

Similar to the analysis from above, the impact of tilting of the collimating lens was evaluated. The results for the analysis of the beam path at 1.55 µm is omitted, because it is similar to the result presented above for the collimating lens due to the symmetry of the beam collimation and focusing for 1.55 µm. The results for the dependency of the fiber coupling efficiency and the wavefront aberration on the focusing lens tilt angle for the two other wavelengths are shown in Figure 23. Again, 1.064 µm is slightly more sensitive to tilts than the other wavelengths, although here the aberrations for tilts up to 1.5° are tolerable for all wavelengths.
3.4.3 Tolerance to Defocus of the Focusing Lens

In Figure 21 the coupling efficiency and the wavefront aberrations are plotted vs. the distance of the photonic crystal fiber from the focusing lens (a distance of 100 mm is the nominal design). It is evident that in general the distance between the lens and the fiber tip must be maintained with a precision of 50 µm to keep the coupling at a good level; for 0.532 µm the tolerance could be slightly relaxed. These results are in good agreement with the predictions obtained by calculating the real defocus of the beam as shown in section 2.4, chapter 2. An interesting point to note here is that the best coupling
efficiency does not necessarily correspond to a minimum wavefront error as can be seen from the plots for 1.064 \textmu m. This indicates that optimal coupling efficiency is obtained here while balancing wavefront errors and the mismatch between the beam size and the mode field size.

### 3.4.4 Tolerance to Focusing Lens Decentering

The results from an evaluation of the fiber coupling system’s tolerance to decentering (lateral shifting) of the focusing lens are depicted in Figure 22. The curves of the coupling efficiency vs. lens shift demonstrate that a decenter of up to 0.5 mm is tolerable with negligible impact on performance for all three wavelengths. Interestingly, the beam at 1.064 \textmu m is slightly less sensitive to decenter than the other wavelengths, while it was the most sensitive to collimating lens tilt.
Figure 21: The fiber coupling efficiency and the peak to valley wavefront error vs. the distance between the focusing lens and the photonic crystal fiber for the three wavelengths 1.55 µm (a), 1.064 µm (b), and 0.532 µm (c).
Figure 22: The coupling efficiency and the peak to valley wave front vs. the decenter of the focusing lens is plotted for the three wavelengths 1.55 µm (a), 1.064 µm (b), 0.532 µm (c).
In summary, the most important result of the tolerance analysis is that the beam path at 1.064 µm is more sensitive to tilt of the collimating lens than the paths at 1.55 and 0.532 µm. This is because for 1.064 µm large coma is introduced in the wave front. Note that Zemax therefore underestimates the fiber coupling efficiency, because it assumes the center of the mode field at the chief ray. For coma the chief ray intersects the image plane at the tip of the cone pattern. Hence, Zemax optimizes the fiber coupling values using the tip of the cone as the center rather than the beam centroid. In contrast, for the 0.532 µm beam path astigmatism is introduced. In this case Zemax calculates the values with respect to the chief ray that is close to the beam centroid.

3.5 Alternative Designs Considered for the Fiber Coupling System

In the initial stages of the optical design of the fiber coupling system, a number of alternative design approaches were studied. One idea was to not collimate the beams at all, but use just one single lens to image the source fiber tip onto the tip of the photonic crystal fiber. The first problem we encountered with this approach lies in finding an appropriate lens that provides reasonably low wave front distortions and good fiber coupling efficiency. There are not many off-the-shelf lenses that are optimized for a finite/finite conjugate ratio and if they are available then mostly for 1:1 imaging at short distances. A workaround to this problem was to use the combination of two achromatic doublets.

A second problem arises from the fact that for a system for all three wavelengths the beam combiners (beam splitters) must be placed in the diverging or converging beam, which causes aberrations. If we consider the beam path for 1.55 µm and place plate beam
splitters for beam combination in the converging beam after the achromatic lens pair as shown in Figure 23, then the coupling efficiency was reduced to 30% due to the astigmatism and higher non-rotationally symmetric aberrations introduced by the tilted parallel plates.

Figure 23: Partial schematic of a fiber coupling system with the two plate beam splitters BS$_1$ and BS$_2$ placed in the converging beam close to the photonic crystal fiber (PCF). The re-imaging lens is actually formed by a pair of achromatic doublets (Lens L$_1$). SMF is the single-mode fiber.

Another alternative design that uses cube beam splitter instead of plate beam splitters was also analyzed as shown in Figure 24. Cube beam splitters can introduce only rotationally symmetric aberrations and cause, in general, less problems for wavefronts even if they are placed in divergent or convergent beams. However, this design requires custom dichroic cube beam splitters and the approach was thus not practicable. Another problem is related to space constraints in the convergent beam. It would be quite difficult to mechanically mount two beam splitters with the necessary mount and alignment hardware between the focusing lens and the tip of the photonic crystal fiber.
3.6 Optical Design of an Apochromatic Lens for the Polychromatic Fiber Collimator

After combining all three wavelengths into a single photonic crystal fiber a fiber collimator is needed to transmit all three beams as collimated beams of the polychromatic laser beacon. To prevent chromatic aberration either a parabolic mirror or an apochromatic lens are possible solutions for the collimating element. Apochromats are designed to bring three wavelengths into focus in the same plane while the popular achromatic doublets have only two wavelengths with identical focal length. Moreover, the addition of the third element controls both spherochromatism and zonal spherical aberrations in addition to primary aberrations such as chromatic, coma and spherical aberrations. In order to correct for secondary spectrum, optical glasses with special dispersive properties are chosen.

For evaluation of a possible solution, an apochromat with a diameter of 33 mm and a focal length of 150.4 mm was designed using Zemax. Conventional crown and flint
glasses, namely N-BK7 and F2, were chosen from the Schott catalogue for the first two elements. For the third element extra low dispersion glass FPL-53 from the Ohara catalogue was chosen which lies further away from the normal glass line [24]. FPL-53 is a fluoride glass which has low dispersion properties that help reduce the secondary spectrum. The problem is these glasses have high fluoride content which can be soft and fragile and can crack due to environmental influences. Hence this glass was placed as the second element in the design to be protected by the two other lens elements. The radius of curvature for each of the elements was optimized in Zemax. This design has been modified from a design suggested earlier [25]. This apochromat used the low dispersion crown glass BK3 and a high dispersion short flint glass N-SF57 for the first two elements. The third element, FPL-53, is common with both the designs.

The lens prescription and its specifications are shown in (Table 5, Table 6). The entrance pupil diameter for the three wavelengths (1.55, 1.064 and 0.532 µm) is calculated as 33.3 mm, 22.7 and 10.2 mm respectively. A drawing of the lens is shown in Figure 25.

![Figure 25: Lens drawing of the apochromat with an effective focal length of 150.4 mm and a back focal distance of 146.54 mm.](image)
The collimator for the PCF will also be equipped with a fiber positioner that can cause beam pointing deviation within a range of ±0.5 mrad from the optical axis (and potentially more in future versions). Therefore, in order to consider the off-axis performance in the design process, a maximum field of view of 0.1° (which corresponds to 1.74 mrad) was introduced. The wave front (measured in waves) and the Strehl ratio obtained are shown in Table 7. From the table, we see that the wave front on-axis performs well. The off-axis performance at 0.1° is $\lambda/11$ for 1.55 µm, $\lambda/33$ for 1.064 µm and $\lambda/125$ for 0.532 µm which is good considering that the wavelengths extend from 0.532 µm to 1.55 µm. The wave front is shown in Figure 26 and Figure 27 for the on-axis and off-axis performances respectively.
Table 6: Lens prescription with the specifications.

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective focal length, EFL (mm)</td>
<td>150.44</td>
</tr>
<tr>
<td>Distance from the fiber to the first surface of the lens (mm)</td>
<td>146.54</td>
</tr>
<tr>
<td>Numerical aperture (F-number)</td>
<td>0.113 (F/4.5)</td>
</tr>
<tr>
<td>Half field of view, HFOV (in degrees)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 7: On-axis and off-axis performance of the apochromat with a HFOV at 0 and 0.1° respectively.

<table>
<thead>
<tr>
<th>Wave-length, $\lambda$ ($\mu$m)</th>
<th>1.55</th>
<th>1.064</th>
<th>0.532</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strehl ratio, $S_t$ (0° HFOV)</td>
<td>0.99</td>
<td>0.99</td>
<td>1.0</td>
</tr>
<tr>
<td>Strehl ratio, $S_t$ (0.1° HFOV)</td>
<td>0.99</td>
<td>0.99</td>
<td>1.0</td>
</tr>
<tr>
<td>Wave front error, peak-to-valley, (waves), (0° HFOV)</td>
<td>0.01</td>
<td>0.009</td>
<td>0.004</td>
</tr>
<tr>
<td>Wave front error, peak-to-valley, (waves), (0.1° HFOV)</td>
<td>0.09</td>
<td>0.03</td>
<td>0.008</td>
</tr>
</tbody>
</table>
Figure 26: On-axis (0° HFOV) wave front of the apochromatic collimator described in (Table 5) at 1.55 µm (a), 1.064 µm (b), and 0.532 µm (c).
Figure 27: Off-axis (0.1° HFOV) wave front of the apochromat collimator lens at 1.55 µm (a), 1.064 µm (b), and 0.532 µm (c).
Alternative designs were also considered. For instance, FPL-53 can be replaced with a more common Fluoro/phosphate glass such as N-FK51A which is less expensive and more readily available (Schott catalogue). After optimization of the lens surface curvatures in Zemax the following on-axis peak to valley wave fronts were calculated: $\lambda/12$ for 1.55 µm, $\lambda/18$ for 1.064 µm and $\lambda/34$ for 0.532 µm. The off-axis performance at $0.1^\circ$ was about $\lambda/5$ for 1.55 µm, $\lambda/8$ for 1.064 µm and $\lambda/27$ for 0.532 µm. The Strehl ratio was greater than 0.98 for all three wavelengths. The lens prescription and its specifications are shown in (Table 8, Table 9). Comparing the peak to valley wave front aberrations, the former design performs better than the latter; however in the latter design FK51A is a more commonly available glass than FPL-53.

Flint glass F2 can also be replaced by a short flint glass such as N-KZFS4, which has a much stronger deviation of the partial dispersion from the normal line. These glasses are suited for apochromat designs and can be used in combination with N-FK51A for color correction as shown in (Table 10, Table 11). The Strehl ratio was greater than 0.99 for all three wavelengths for the on-axis performance. The off-axis performance was also greater than 0.99 for the three wavelengths. The wave front aberrations was calculated as $\lambda/18$ for 1.55 µm, $\lambda/42$ for 1.064 µm and $\lambda/286$ for 0.532 µm at $0^\circ$ and at $0.1^\circ$ the peak to valley wave front was calculated as $\lambda/10$ for 1.55 µm, $\lambda/40$ waves for 1.064 µm and $\lambda/179$ waves for 0.532 µm. The problem with these glasses is that short flints are more expensive and when combined with low dispersion glasses such as N-FK51A and FPL-53 the collimation lens can be even more expensive. In summary, an apochromatic collimator lens with very good wavefront quality is feasible, but involves custom lens elements. The apochromat would be an ideal solution for the collimating
element as it requires less space and is easier to align compared to a collimator based on an off-axis parabolic mirror. However, in order to avoid the custom manufacturing of the collimator lens for setting up a laboratory prototype, the apochromat has not been built and it was decided to go with an off-axis parabolic mirror, which was available in the laboratory.

Table 8: Lens prescription for an f/4.5 0.1 degree HFOV apochromat. All lens units are in mm.

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Index</th>
<th>V-no</th>
<th>Semi-Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object (fiber tip)</td>
<td>-</td>
<td>154.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.27</td>
</tr>
<tr>
<td>1</td>
<td>60.04</td>
<td>6.0</td>
<td>F2</td>
<td>1.62</td>
<td>36.37</td>
<td>20.0</td>
</tr>
<tr>
<td>2</td>
<td>42.42</td>
<td>5.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20.0</td>
</tr>
<tr>
<td>3</td>
<td>46.87</td>
<td>10.0</td>
<td>N-FK51A</td>
<td>1.49</td>
<td>84.47</td>
<td>20.0</td>
</tr>
<tr>
<td>4</td>
<td>-46.92</td>
<td>7.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20.0</td>
</tr>
<tr>
<td>5</td>
<td>-37.64</td>
<td>7.0</td>
<td>N-BK7</td>
<td>1.52</td>
<td>64.17</td>
<td>20.0</td>
</tr>
<tr>
<td>STOP</td>
<td>-245.53</td>
<td>30.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20.0</td>
</tr>
<tr>
<td>IMAGE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>16.45</td>
</tr>
</tbody>
</table>

Table 9: Lens prescription with the specifications.

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective focal length, EFL (mm)</td>
<td>150.57</td>
</tr>
<tr>
<td>Distance from the fiber to the first surface of the lens (mm)</td>
<td>154.6</td>
</tr>
<tr>
<td>Numerical aperture (F-number)</td>
<td>0.102 (F/4.5)</td>
</tr>
<tr>
<td>Half field of view, HFOV (in degrees)</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Table 10: Lens prescription for an f/4.5 0.1 degree HFOV apochromat. All lens units are in mm.

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Index</th>
<th>V-no</th>
<th>Semi-Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object (fiber tip)</td>
<td>-</td>
<td>129.44</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.23</td>
</tr>
<tr>
<td>1</td>
<td>130.54</td>
<td>6.0</td>
<td>N-KZFS4</td>
<td>1.61</td>
<td>44.49</td>
<td>20.0</td>
</tr>
<tr>
<td>2</td>
<td>43.47</td>
<td>5.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20.0</td>
</tr>
<tr>
<td>3</td>
<td>54.85</td>
<td>9.5</td>
<td>N-FK51A</td>
<td>1.49</td>
<td>84.47</td>
<td>20.0</td>
</tr>
<tr>
<td>4</td>
<td>-49.29</td>
<td>5.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20.0</td>
</tr>
<tr>
<td>5</td>
<td>-65.98</td>
<td>6.0</td>
<td>N-BK7</td>
<td>1.52</td>
<td>64.17</td>
<td>20.0</td>
</tr>
<tr>
<td>STOP</td>
<td>-121.79</td>
<td>30.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20.0</td>
</tr>
<tr>
<td>IMAGE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>19.28</td>
</tr>
</tbody>
</table>

Table 11: Lens prescription with the specifications.

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective focal length, EFL (mm)</td>
<td>149.81</td>
</tr>
<tr>
<td>Distance from the fiber to the first surface of the lens (mm)</td>
<td>129.44</td>
</tr>
<tr>
<td>Numerical aperture (F-number)</td>
<td>0.13 (F/4.5)</td>
</tr>
<tr>
<td>Half field of view, HFOV (in degrees)</td>
<td>0.1</td>
</tr>
</tbody>
</table>
CHAPTER 4
SETUP OF A LABORATORY PROTOTYPE FOR THE FIBER COUPLING SYSTEM AND THE POLychROMATIC BEACON COLLIMATOR

This chapter describes the setup of a breadboard prototype of the fiber coupling system, the measurement of coupling efficiencies, the calculation of system losses, and tests that demonstrate the fiber coupling system’s compensation of mechanical distortions.

4.1 Fiber Coupling Prototype System Assembly

Before assembly of a prototype of the poly-chromatic fiber-coupling system, preliminary tests for each of the channels (wavelengths 1.55, 1.064, and 0.532 µm) were performed. The goal was to test the fiber coupling with the selected lenses for each wavelength and show that it is comparable to the theoretical values obtained using ray-tracing with the optical design software Zemax. As later in the full system, fiber-positioners based on piezo-electric actuators were used for optimum positioning of the transmitting fiber tips. These fiber positioners were inserted into special compact mounts, which provide six degrees of freedom for the angular and position alignment of the fiber-tip [26] (these alignment mechanisms were only used for coarse alignment). The fiber
positioners, together with these mounts, were inserted into variable lens holders. The collimating lens was mounted in a lens holder on a Z-translation stage to adjust focus. At the receiver side, the focusing lens was mounted on a stationary platform and the photonic crystal fiber (held in a bare-fiber adapter) was mounted on an X, Y, Z translational stage. The PCF was fixed at a distance of 100mm from the collimating lens in the test setups for all three wavelengths, the same value as in the optical design described in Chapter 3.

Alignment and fiber-coupling tests were aided using the fiber positioners and the INFOCO controllers, which utilize the stochastic parallel gradient decent (SPGD) algorithm. The power coupled into the PCF was measured at the PCF exit using a photodetector and its output voltage was used as feedback signal (performance metric) for the INFOCO controller. The fiber positioner and controller were helpful during the alignment procedure in two ways. First, an automatic two dimensional scanning of the fiber tip over the whole range of lateral positions that is reachable with the fiber actuators helped to find a position of the fiber tip such that at least a part of the transmitted light is coupled.

Figure 28: Photos of the setup used for preliminary closed loop tests with the 0.532 µm fiber positioner with no beam splitters in the path using INFOCO controller to optimize the fiber coupling efficiency as shown in (a). At the receiver side the photonic crystal fiber is mounted on a translational stage and the output of the fiber using the 0.532 µm laser is shown in (b).
into the PCF. This scanning is a function implemented in the controller. Second, once the light coupled into the PCF was detectable by the photodiode, the feedback control system optimized the lateral position of the source fiber for coupling of the beam into the photonic crystal fiber. Then the optimal focus can be found by manually changing the fiber position along the Z axis. Feedback control automatically adjusts the X and Y position while manually changing the Z position and thus compensates for slight misalignments of the translation stage, i.e., non-parallelism of the translation stage Z axis and the optical axis (until larger corrections with the manual translation stage are necessary).

After demonstrating that the achieved coupling efficiencies were in reasonable agreement with the values expected from the optical design (fiber coupling measurements are discussed in detail in Section 4.2 below), the complete fiber coupling system prototype was assembled on a 1×2 feet, 2-inch thick optical breadboard using the optical design described in Section 3.3, Figure 17 as basis. The positioner for each source fiber was mounted on a three-axis manual translation stage with a custom mounting adapter. The translation stages were used to perform the alignment of the fiber tip with respect to the collimating lens. The photonic crystal fiber (PCF) was also mounted on a translational stage with a bare fiber holder in a FC/PC connector. The position of the receiving fiber tip (i.e. the input end of the photonic crystal fiber) was not actively controlled with a fiber positioner. The focusing lens was positioned at a fixed distance of 100 mm in front of the PCF. A photo of the prototype system is shown in Figure 29.
Figure 29: Prototype of the fiber coupling system for combining light of three wavelengths (1.55, 1.064 and 0.532 µm) into a single photonic crystal fiber.

The alignment strategy was as follows: First the coupling for 1.55 µm was established. It is the path that goes straight through the dichroic beam splitters (with a lateral shift by 6.8 mm caused by the beam splitter plates). After this path was optimized, the fiber collimators for the other two wavelengths (1.064 and 0.532 µm) were set up. Their alignment was performed using only the translation stage with the respective fiber positioner and the fiber positioner itself. The translation stage with the PCF wasn’t moved in this phase of the alignment procedure, because this would have destroyed the alignment of the 1.55 µm path.
4.2 Fiber Coupling System Evaluation

4.2.1 Fiber Coupling Efficiency Measurements

To determine the efficiency of coupling light into the PCF, one has to measure the power of the light emerging from the PCF and compare it to the power of the light incident to the PCF. In the experimental setup the measurement of the incident light was cumbersome, because a detector with a sufficiently large sensor area was not available for all wavelengths and the detector could not be placed close enough to the PCF to collect all the light. Removing the FC/PC fiber adapter mounted onto the translation stage that holds the PCF was also not an option, because it would have destroyed the alignment of the PCF. Placing a mirror in front of the PCF at an angle of about 45° and putting the detector close to the focal plane as shown in Figure 30 is a viable solution. However, the disadvantage of using a mirror is that the detector needs to be well aligned in front of it so that the focused beam hits the detector’s sensor each time a measurement is taken.

![Figure 30: Setup for fiber coupling efficiency measurements. The beams are intercepted after passing through the focusing lens $L_2$ by a mirror oriented at about 45° and focused onto a detector.](image-url)
A more practical solution was to take the PCF with its bare fiber adapter out of the FC/PC adapter on the translation stage and temporarily replace it with a connectorized multi-mode (MM) fiber with a large core (200 µm diameter). The large core of the MM fiber was expected to be sufficient to collect all light incident on the fiber tip. To accurately compare the two methods (mirror insertion vs. measurement with MM fiber) one has to consider the reflection of light upon entering and exiting the fiber. The portion of reflected light is given by the Fresnel coefficient [4]

\[
R = \left( \frac{n_1 - n}{n_1 + n} \right)^2.
\]  

(28)

Here \(n_1\) is the refractive index of the fiber core (for silica \(n_1 = 1.44\)) and \(n\) is the refractive index of air (\(n \approx 1\)). Thus about 3.3% of the light is reflected at each fiber end and a total of \((1 - R)^2 = 93.6\%\) of the incident power can be transmitted by the fiber. This transmission factor applies to the MM fiber and the PCF. Taking the reflection at the fiber tips into account, tests performed with the 1.55 µm path resulted, within the margin of error, in the same coupling efficiency for the measurements with the MM fiber and the setup using the mirror as shown in Figure 30.

The measured coupling efficiencies \(\eta_{\text{meas}}\) for each wavelength are compared with the theoretical efficiencies predicted by Zemax \(\eta_{\text{Zemax}}\) in Table 12.
Table 12: Comparison between the theoretical and experimental coupling efficiencies.

<table>
<thead>
<tr>
<th>Wavelength, ( \lambda ) (( \mu )m)</th>
<th>1.55</th>
<th>1.064</th>
<th>0.532</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling Efficiency, ( \eta_{\text{meas}} ) (%)</td>
<td>83.4</td>
<td>50</td>
<td>70.4</td>
</tr>
<tr>
<td>Coupling efficiency, calculated with Zemax, ( \eta_{\text{Zemax}} ) (%)</td>
<td>82.8</td>
<td>95.1</td>
<td>93.5</td>
</tr>
</tbody>
</table>

The coupling efficiencies measured are, in general, in reasonably good agreement with the theoretical values obtained with Zemax. However, the coupling efficiency for 1.064 \( \mu \)m is reduced to about 50% that of the predicted value due to two reasons. One, the wave front aberration of the lens is considerably larger than the other two wavelengths (a wave front distortion of 3.4 waves was measured using an interferometer). Second, based on the tolerance analysis from Section 3.4, it was found that 1.064 \( \mu \)m was most sensitive to tilt of the collimating lens and defocus. For 0.532 \( \mu \)m, the coupling efficiency is slightly lower than the theoretical result, whereas the coupling efficiency for 1.55 \( \mu \)m agrees well with the predicted value. The fact that the measured value is actually slightly higher than the predicted value may be due to the experimental errors, caused, for instance, by laser power fluctuations, tolerances of the specifications of the PCF. Moreover, the mode field diameter for the photonic crystal fiber (ESM-12B) specified by the manufacturer is 10 \( \mu \)m within a tolerance range of \( \pm 1 \) \( \mu \)m. The true diameter can be anywhere within this range and hence the calculations with Zemax may be based on inaccurate value for the mode field diameter.
4.2.2 Estimation of System Throughput

The efficiency of transmitting light from a laser source into the photonic crystal fiber through the free-space fiber coupling system is impacted by various loss factors: efficiency of coupling into the PCF, reflection losses from lens surfaces, transmission or reflection factors of the dichroic beam splitters, and reflection at fiber tips. In order to calculate the overall link loss budget as the sum of all the loss contributions from each element in the link, the loss elements \( L_s \) are expressed in decibels (dB) given as \([4]\),

\[
L_s(\text{dB}) = 10 \log \frac{P_{out}}{P_{in}}
\]  

(29)

where \( P_{out} \) and \( P_{in} \) are the optical powers in and out of the loss elements. The reflection losses at glass/air interfaces are calculated using Equation (28). In addition there may be insertions losses in fiber-to-fiber connectors used to connect the source laser to the fiber in the fiber positioner which are given in the manufacturer’s specifications. All estimates for loss contributions in the polychromatic fiber coupling system are summarized in Table 13.
Table 13: Estimates for losses in the fiber coupling system for all three wavelengths.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>1.55 µm</th>
<th>1.064 µm</th>
<th>0.532 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%)</td>
<td>(dB)</td>
<td>(%)</td>
</tr>
<tr>
<td>1.</td>
<td>Single-mode fiber to fiber connector (maximum insertion loss)</td>
<td>10.9</td>
<td>-0.5</td>
</tr>
<tr>
<td>2.</td>
<td>Single-mode fiber output</td>
<td>3.3</td>
<td>-0.15</td>
</tr>
<tr>
<td>3.</td>
<td>Collimating lens first surface, L₁a, L₁b, L₁c</td>
<td>4.2</td>
<td>-0.19</td>
</tr>
<tr>
<td>4.</td>
<td>Collimating lens second surface, L₁a, L₁b, L₁c</td>
<td>5.6</td>
<td>-0.25</td>
</tr>
<tr>
<td>5.</td>
<td>Focusing lens first surface, L₂</td>
<td>4.2</td>
<td>-0.19</td>
</tr>
<tr>
<td>6.</td>
<td>Focusing lens second surface, L₂</td>
<td>5.6</td>
<td>-0.25</td>
</tr>
<tr>
<td>7.</td>
<td>First beam splitter (two surfaces), BS₁</td>
<td>5</td>
<td>-0.22</td>
</tr>
<tr>
<td>8.</td>
<td>Second beam splitter (two surfaces), BS₂</td>
<td>5</td>
<td>-0.22</td>
</tr>
<tr>
<td>9.</td>
<td>PCF fiber input</td>
<td>3.3</td>
<td>-0.15</td>
</tr>
<tr>
<td>10.</td>
<td>PCF fiber output</td>
<td>3.3</td>
<td>-0.15</td>
</tr>
<tr>
<td>11.</td>
<td>Total estimated reflection losses, Lₑₑₑ</td>
<td>40.5</td>
<td>-2.25</td>
</tr>
</tbody>
</table>

Table 13 shows that the channel at 0.532 µm has the highest total insertion/reflection loss due to the insertion loss (more than half of the light from the laser), mostly due to the large estimate for the insertion loss in the fiber-to-fiber connector. However, the data provided in the specification sheet show the worst-case estimate and the real value may be considerably smaller.

The theoretical (or estimated) optical throughput of the system, $S_{\text{theor}}$, can be calculated as the product of Zemax’s coupling efficiency, $\eta_{\text{Zemax}}$, and the estimate of
the fraction of light that is not reflected, that is \((1 - L_{est})\). In Table 14, these values are compared with the experimental values \(S_{meas}\) obtained as ratio of the total power emerging from the photonic crystal fiber to the power provided by the laser.

Table 14: Comparison between the measured and theoretical coupling values for the optical throughput for all three wavelengths.

<table>
<thead>
<tr>
<th>Wavelength, (\lambda) ((\mu)m)</th>
<th>1.55</th>
<th>1.064</th>
<th>0.532</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical throughput, (S_{ theor}) (%)</td>
<td>49.3</td>
<td>61.6</td>
<td>42</td>
</tr>
<tr>
<td>Measured throughput, (S_{meas}) (%)</td>
<td>49.6</td>
<td>32.4</td>
<td>31.6</td>
</tr>
</tbody>
</table>

As can be seen from Table 14, the system throughputs for 1.55 \(\mu\)m and 0.532 \(\mu\)m measured experimentally are in reasonably good agreement with the theoretical predictions, whereas the experimental throughput for 1.064 \(\mu\)m is reduced to half that of the theoretical value due to the reasons discussed in Section 4.2.1 (aberrations of the collimating lens, higher sensitivity to misalignments).

### 4.3 Supplemental Evaluation of the Photonic Crystal Fiber

#### 4.3.1 Mode Field Diameter Measurements

The specifications for the endlessly single-mode photonic crystal fiber in the Thorlabs catalog claim the ESM-12B large mode area photonic crystal fiber is truly single mode for all three wavelengths considered here. According to these specifications, the mode profile is very similar to the quasi-Gaussian fundamental mode of a
conventional axially symmetric step index fiber resulting in a form overlap that is greater than 90% [27].

To check whether the fiber is truly single-mode for all wavelengths as claimed in the specifications, near-field and far-field measurements were performed using a laboratory based microscope to measure the real beam profile exiting out of the fiber.

The photonic crystal fiber tip was re-imaged using a 20X microscope objective. A white light source was placed close to the fiber tip to capture images of the photonic crystal fiber tip that were used for scaling of the image (the diameter of the fiber tip is known to be 125 µm). A camera (DCC1545M Thorlabs monochrome sensor) with a resolution of 1024 by 1280 pixels was connected to the microscope tube. This camera measured only 1.064 and 0.532 µm. Another camera (SU640KTSX InGaAs Sensors Unlimited) was used to record images for 1.55 µm. The near-field images and their corresponding beam profiles for all three wavelengths are shown in Figure 31.
4.3.2 Far-field Measurements

The far-field beam profiles are compared for two wavelengths (1.55 µm and 1.064 µm) as shown in Figure 33. The goal of these measurements was to examine if the
far-field diameter of 1.064 µm is about two-thirds that of 1.55 µm as expected if the beams have the same diameter at the fiber. (Due to insufficient laser power, measurements for 0.532 µm could not be taken. Hence only two wavelengths are considered here.) The tip of the light emitting photonic crystal fiber was mounted on a post in front of a detector. A pinhole was fixed on the detector so that light falling on the detector could be adjusted. As the detector was moved laterally its corresponding output voltage was measured. The schematic and a picture of the setup are shown in Figure 32.

![Diagram](image.png)

**Figure 32:** Schematic (a) and picture (b) of the far-field beam profile measurements with a pinhole and a detector placed in the beam exiting out of the photonic crystal fiber.

The measurements were noisy due to the low power level transmitted by the pinhole and fluctuations of the laser power. The resulting far-field beam profiles were approximated by a Gaussian profile as shown in Figure 33.
Figure 33: Far-field beam profile measurements taken for 1.55 and 1.064 µm, shown in (a) and (b), respectively.

The beam radii $w_0$ (at the $1/e^2$ level) for 1.55 µm and 1.064 µm were determined from the Gaussian fit curves as 2.68 and 1.80 µm respectively. Comparing the ratios of these two wavelengths and the corresponding beam radii we get values of 1.46 and 1.49 respectively. Thus, these values confirm that the far-field beam diameter is approximately proportional to the wavelength, which in turn means that the beam diameter at the fiber tip is roughly the same.
4.4 Beacon Collimator Subsystem Assembly

In order to avoid the delays and expenses related with the manufacturing of a custom apochromatic lens, a solution using an off-axis parabolic mirror (OAP-15-1.25-2.0) in the laboratory prototype for the polychromatic beacon collimator was considered. A mirror with a diameter of 2 inches (50.8 mm), focal length of 15 inches (381 mm), and an off-axis distance of the focus of 2.25 inches (57.15 mm) manufactured by Space Optics Research Lab (SORL) was available for the project. The f-number of the mirror is 7.5, which is bigger than the ideal range of 4.5 to 5 determined by the divergence of the transmitted beams. This and the fact that not the full mirror aperture was used in the final setup resulted in considerably more beam truncation than the apochromatic lens would cause.

The off-axis parabolic mirror together with a fiber positioner with an ESM-12B photonic crystal fiber was mounted onto a 1×2 foot optical breadboard. This separate optical platform allowed for mounting of the beacon collimator on a gimbal, which will be necessary if it is to be used in atmospheric propagation experiments. To achieve a good beam quality, the fiber tip of the PCF needs to be located in the focal point of the off-axis parabolic mirror within $\lambda/10$ waves. The fiber positioner was thus mounted onto a three-axis translation stage for fiber alignment in similar way as the source fibers in the fiber coupling system (Figure 34). In addition, this translation stage was equipped with a tip/tilt platform, which allowed for pointing of the beam onto the center of the off-axis mirror.
For the alignment process, light of a He-Ne laser with a wavelength of 0.633 µm from an Interferometer (ESDI Z100) was coupled into the PCF using the parabolic mirror. The mirror was aligned using an alignment flat mounted on the circumference of the mirror perpendicular to the optical axis of the beam. The collimated laser beam from the interferometer was reflected off the parabolic mirror and coupled into the PCF. Light coupled into the fiber was optimized using the X, Y, Z axis of the translation stage and measured using a detector. For fine alignment, INFOCO controller with a feedback loop was used to optimize the coupling efficiency. In order to have the beam collimated from the off-axis mirror and measure the quality of its wavefront, a fiber coupled laser diode from Thorlabs (S1FC635) with a wavelength of 0.635 µm was used as a source connected to the PCF. The quality of the wavefront of the beam reflected off the parabolic mirror was evaluated using a shearing interferometer from Thorlabs (SI500). Optimization of the alignment was performed until the beam was collimated with wave front aberrations significantly less than a wavelength. A photo in Figure 35 shows the interference fringe pattern generated by the shear plate after the alignment procedure. It indicates that the aberrations were a quarter of a wavelength or less.
Figure 34: Photo of the polychromatic beacon setup taken in the laboratory. OAM is the off-axis parabolic mirror which collimates the three wavelengths. PD$_1$ and PD$_2$ are photo detectors (consisting of a photo diode and an amplifier) used for feedback. PD$_1$ is used for 1.55 and 1.064 µm and PD$_2$ is used to measure 0.532 µm.

Figure 35: The beacon is aligned using an off-axis parabolic mirror mounted on a breadboard. A shearing interferometer from Thorlabs (SI500) with a 25.4-50 mm beam diameter shear plate was used to collimate the beam.
CHAPTER 5
MULTI-WAVELENGTH ADAPTIVE FIBER COUPLING WITH PIEZOELECTRIC FIBER POSITIONERS

In the polychromatic beacon system the INFOCO controllers use the SPGD algorithm described in Section 2.5.2 to maximize the optical power that is coupled into the photonic crystal fiber (and is then emerging from the collimator) by optimizing the lateral position of the source fibers in the fiber coupling system using the piezoelectric fiber positioners. In each iteration step of the stochastic parallel gradient descent (SPGD) control algorithm, small random perturbations are added to the control voltages of the fiber positioners, the corresponding changes in the emerging power are measured, and these changes are used to update the control voltages. Because there needs to be a feedback loop for positioning of all three source fibers, different architectures for the feedback loop may be considered. These are discussed in Section 5.1. The initial demonstration of simultaneous feedback control for the coupling of all three wavelengths into the photonic crystal fiber is described in Section 5.2. Results from the evaluation of the feedback control performance in the presence of external distortions (vibration) are presented in Section 5.3. Solution for incorporating feedback sensors into the PCF collimator are discussed in Section 5.4.
5.1 Feedback Loop Architectures

Having in mind the best performance of the adaptive fiber coupling system, the arguably optimal feedback architecture would consist of three completely independent feedback loops, one each for each wavelength, with dedicated detectors that measure the amount of light coupled into the PCF at the three wavelengths separately. Each control loop would thus have its own performance metric and the control loops could not interfere with each other. From a practical point of view, this is not the most elegant solution, because splitting up the light for three different detectors requires two beam splitters and laser-line filter in front of each detector to provide really independent metrics.

One could also envision a control system with a single detector that works for all three wavelengths. Such architecture would reduce the need for beam splitters and filters, but would require that optimization at all three wavelengths are performed with a single metric. This can be done with a single SPGD controller that synchronously controls several fiber positioners in parallel (similar to the tip/tilt control used for fiber collimator arrays [28]. However, it was shown that asynchronous wave front control with multiple SPGD controllers that use the same performance metric is possible [29]. Thus it is possible to use three different controllers – each controlling one source fiber positioner – in parallel without the need for synchronization of the iterative control. It is expected that the convergence of SPGD optimization for both cases synchronous or asynchronous control is somewhat reduced in comparison to completely independent control loops due
to a larger number of control channels or the interference between control loops, respectively.

Because of the limited sensitivity range of the usual photo-detector materials – Silicon (Si) for visible to NIR light (190 to 1100 nm) and Indium Gallium Arsenide (InGaAs) for NIR (800 to 1700 nm) – a single detector that covers the full spectrum of wavelengths for the polychromatic beacon has not been available. However, in principle it is possible to generate a single performance metric by combining the photocurrent outputs of dual-layer photo detectors, such as the Thorlabs DSD2 photodiode [27] with a Si substrate above an InGaAs substrate, which would cover the whole range of wavelengths relevant for the polychromatic beacon.

In order to use photo-detectors already available in the laboratory, the feedback loop configuration used in the prototype system is a hybrid solution between the approaches discussed above and uses two detectors and two metric signals. A beam splitter was used to split the light used for feedback between the two detector areas. An InGaAs photodiode (PD₁) determines the power of the light at 1.55 µm and 1.064 µm. The output voltage of its transimpedance amplifier was used as metric $J_1$ for the two SPGD controllers that drive the fiber positioners with the source fibers for 1.55 µm and 1.064 µm. A Si photodiode (PD₂) with a transimpedance amplifier was used to provide the metric $J_2$ for the controller for the 0.532 µm source fiber positioner. Initial testing of the feedback control was performed without connecting the PCF to the beacon collimator. Instead, the whole output light of the PCF was directed towards the detectors as shown in Figure 36.
Figure 36: Schematic of the fiber coupling system with feedback loops using two photo detectors PD$_1$ and PD$_2$. The InGaAs detector PD$_1$ and the corresponding metric $J_1$ is used by two simultaneously operating SPGD controllers to optimize coupling of the light at 1.55 and 1.064 µm into the photonic crystal fiber (PCF). The Si detector PD$_2$ determines the metric $J_2$ used for optimizing coupling of light at 0.532 µm. A cube beam splitter placed in the divergent beam that is emerging from the PCF splits the light for the two detectors. Due to its small sensing area (diameter 1 mm), a lens was needed to focus the light onto the detector PD$_1$.

5.2 Demonstration of Simultaneous Fiber Coupling Optimization with Three Wavelengths

For stabilization of the fiber coupling, commercially available controllers implementing a two-channel version of the SPGD control algorithm described in Section 2.5.2 were used. These controllers – referred to as INFOCO controllers – use an Ethernet interface to connect to a PC with the graphical user interface (GUI) of the control software. A screenshot of the GUI is shown in Figure 37.
Several SPGD parameters can be controlled through the GUI. The magnitude of the update gain $\gamma$ can be set through the gain scaling factor ($\gamma$ is the same for both channels). Moreover it can be chosen to be either a constant value or an adaptive value that change with the measured metric value $J$ (through a look-up table that can be uploaded to the controller from a file).

The amplitude of the random perturbations of the control parameters is selected through the perturbation scaling factor, here denoted as $\sigma$. By choosing binary mode, the perturbation value is equal to the scaling factor multiplied by either $+1$ or $-1$ so that the
perturbations are statistically independent random “coin-flip” numbers with identical amplitudes $|\delta a_j| = \sigma$ and a Bernoulli probability distribution with $p(\delta a_j = +\sigma) = \frac{1}{2}$ and $p(\delta a_j = -\sigma) = \frac{1}{2}$. [21] [16]. For the Gaussian perturbation mode, the random values have a Gaussian probability distribution. For the “mix perturbation,” the controller starts in binary mode and switches to Gaussian mode after the fiber coupled power (metric $J$) reaches a user-defined threshold value. Gaussian mode and an update gain scaling factor depended on the fiber coupling power (metric $J$) was used in the experiments.

The SPGD cycle duration $T_{SPGD}$, i.e., the time for a single SPGD iteration can also be specified in the GUI. $T_{SPGD}$ determines the delay time $\tau_j$, which corresponds to the time between applying perturbation voltages $a_1^{(n)} \pm \delta a_1^{(n)}$ and measuring the input voltage (metric) response $j_x^{(n)}$.

The “scan” button on the controller software GUI starts a scan through the whole control voltage range for both the X and Y actuators and measures the metric value that corresponds to each fiber position. The metric value as function of the control voltages is then displayed as grayscale image in the graphic box in the left side of the GUI. The scan process locates the position of the maximum fiber coupled power and displays the maximum of $J$ and its corresponding values for X and Y control voltages in the scan results. The graphic box indicates also the current control voltages of the fiber positioner with a blue dot within the grayscale image. When SPGD control is performed, the evolution of the control voltages can be observed here in real time.
In order to demonstrate the simultaneous adaptive coupling of the three laser beams into the photonic crystal fiber with SPGD feedback control the following experiment was performed. Using the manual actuator of the stage on which the photonic crystal fiber was mounted, the tip of the photonic crystal fiber was moved in a lateral direction while all three SPGD control loops were operating simultaneously at slightly different iteration rates of about 2 kHz. To keep the fiber coupling optimized, the positioners need to move the source fibers so that the corresponding beam waist of each beam generated at the PCF follows the movement of the PCF. In the experiment the control voltages were monitored on the GUI for each INFOCO controller. Indeed, when the photonic crystal fiber was moved laterally the positioners for all three wavelengths followed simultaneously and maintained good fiber coupling efficiency. This can be seen in the copies of the GUIs’ graphics windows shown in Figure 38. The images in the left column [(a), (d), and (g)] shows the actuator positions for 1.55 µm at three different times during the experiment. The center column [(b), (e), and (h)] and the right column [(c), (f), and (i)] correspond to 1.064 µm and 0.532 µm, respectively. The top row indicates the position of the source fiber at the beginning of one particular experiment, where the PCF was laterally displaced so that the control voltages for all three wavelengths needed to be off the center position to couple light into the PCF. Because the axes of the fiber positioners were oriented in a random manner, the displacements of the positioners appear under different directions in the GUI window.

After moving the PCF to its central position, all three source fiber positioners move near their respective central position (middle row in Figure 38) and when the PCF was moved further, the fiber positioners followed simultaneously as shown in the bottom
row in Figure 38. As described in the previous sections, the source collimator’s focal length and thus the transverse magnification, $M$, for imaging of the beam waist at the source fiber tip onto the PCF is approximately proportional to the wavelength. $M = 1$ for the path at 1.55 µm and thus the source SMF has to move as much as the PCF to keep the coupling of light into the PCF. For 0.532 µm the magnification is about 3 and thus the source fiber has to move only 1/3 of the distance of the PCF displacement. 1.064 µm is an intermediate case with the movement being reduced by a factor 2/3 in comparison to the PCF. This scaling can be seen in Figure 38, although the factors 1/3 and 2/3 are not exactly met, because of differences in the actuators and because of deviations of the built optical system from the ideal case.
Figure 38: Copies of the graphics window of the INFOCO controllers indicating the lateral position of the source fibers as blue dot within the area that corresponds to the range of X and Y control voltages. Three INFOCO controllers run simultaneously and all three fiber positioners maintain good fiber coupling as the photonic crystal fiber is moved laterally. The left column [(a), (d), (g)] is taken from the controller for 1.55 μm, the center column [(b), (e), (h)] corresponds to 1.064 μm, and the right column to 0.532 μm [(c), (f), (i)]. When images in the top row were taken, the PCF was off center, in the middle row the fiber was moved to the central position and the bottom row corresponds to the case when the PCF was moved further.

5.3 Evaluation of the Performance of the Control Loops in the Presence of Mechanical Distortions

Tests were carried out to ensure the fiber coupling system remained stable even when heavy vibrations were introduced. A power drill was fixed on the breadboard with
the coupling system (Figure 39). Only a single wavelength (1.55 µm) was used for these tests. Turning the power drill on caused strong fluctuations of the performance metric (fiber coupling efficiency). Attempts to mitigate these fluctuations with SPGD optimization of the metric with the INFOCO controllers were not successful. Observations of the metric signal with an oscilloscope showed that it contained strong spectral components at frequencies around 1 kHz. Thus the introduced distortions were too fast to be compensated by the fiber positioner and the SPGD controller, which was operating with iteration rates in the same frequency range (~2 kHz).

In order to check the compensation of vibrations with lower frequency, steel rulers with weights were clamped to the fiber positioners mounted on translation stages as shown in Figure 40. The rulers and weight formed spring-mass oscillators, which performed weakly damped harmonic motions, after the ruler ends with the weights were manually deflected from their equilibrium position. The oscillating rulers transmitted
forces to the flexures of the translation stages and caused thus harmonic motions (vibrations) of the source fiber positions.

Figure 40: Vibration tests performed with steel rulers clamped to fiber positioners for 1.55 µm (i) and 1.064 µm (ii) as shown in (a). The rulers were bent back and forth to produce vibrations within the controller’s frequency range shown in (b).

The plots in Figure 41 show the development of the metric for two experiments with the 1.55 µm and 1.064 µm sources, respectively, in which the feedback loop was switched off for the first 6 seconds and then switched on for the remaining 6 seconds of the trial run while the rulers with the weights were oscillating. It can be seen that the fiber coupling was severely impacted by the vibrations. The metric signal lost a considerable part of the time (the detector bias resulted in a minimum metric signal of about 0.02). When SPGD control was turned after 6 seconds, the metric signal became much more stable with the average values being better than 95% of the measured maximums. The vibration frequencies were 3.8 Hz and 2.5 Hz for the experiments with 1.55 and 1.064 µm respectively. These experiments demonstrated that the compensation of strong mechanical stresses that cause complete loss of the metric signal is possible.
Figure 41: Development of the metric for two experiments with the SPGD control off during the first six seconds and SPGD control on during the next six seconds while vibrations from mechanical forces to the translation stages with the source fibers distorted the fiber coupling system. (a) Experiments were performed with the fiber positioner for 1.55 µm and a vibration frequency of 3.8 Hz; (b) The path for 1.064 µm and a vibration frequency of 2.5 Hz was used.
5.4 Integration of Feedback Signal Measurements into the Photonic Crystal Fiber Collimator

In the integrated polychromatic laser beacon system, the photonic crystal fiber from the beam-combining platform (that is the fiber coupling system) is connected to the fiber-positioner of the collimating platform (beacon collimator assembly). The feedback signal for SPGD control of the fiber positioners need to be determined from the beams emerging from the PCF in the beacon collimator sub-system. This can be done by placing a beam splitter in the collimated beam as shown in the schematic presented in Figure 42. This beam splitter directs a part of the light towards photo-detectors and provides the metric signals for the feedback loops. Such a setup with a beam splitter that reflected nearly 50% of the light was used for the preliminary system demonstration experiments described in Chapter 6.

![Schematic of the beacon with the off-axis parabolic mirror (OAM) and a beam splitter (BS) that transmits the three wavelengths (about 50% of light) for long-distance propagation and reflects 50% of the light on a detector for feedback using a focusing lens.](image)

Figure 42: Schematic of the beacon with the off-axis parabolic mirror (OAM) and a beam splitter (BS) that transmits the three wavelengths (about 50% of light) for long-distance propagation and reflects 50% of the light on a detector for feedback using a focusing lens.
Using a beam splitter in front of the beacon collimator is accompanied by several disadvantages: introduction of wave front distortions from the beam splitter, deflection of the beam if the front and back surface of the splitter are not perfectly parallel, potential interference from reflections inside the splitter and reduction of transmitted power. Hence a setup was developed that uses a spherical positive mirror furnished with a hole in the center to reflect the side tails of the Gaussian beams and to focus this light onto detectors for measurement of the feedback signal (Figure 43). The central part of the beams propagate undistorted through the hole and can be used for long distance propagation. In the laser beacon prototype developed here, the diameter of the mirror was about 3 inches and the focal length was 12 inches. A 1 inch hole in the center under a 5 degree tilt angle was drilled into the mirror by an optics manufacturer. A picture of the laser beacon prototype with the mirror and the detectors is shown in Figure 44. Tests demonstrated that feedback signal for all three wavelengths could be determined with this setup.

In a polychromatic beacon collimator based on an apochromatic lens system, a similar setup for measuring the feedback signals can be introduced. To keep the collimator compact, placing the mirror with the hole into the diverging beams (that is between the PCF and the lens system) would be preferred.
Figure 43: Schematic of the polychromatic beacon with a spherical mirror placed in the collimated beams to focus the Gaussian beam tails onto a detector for feedback signal measurement. OAM is the off-axis parabolic mirror.

Figure 44: Photo of the polychromatic beacon with the off-axis parabolic mirror (OAM) and the mirror with a hole mounted on a breadboard. Photo detectors PD₁ and PD₂ are used to detect light from the Gaussian beam tails at 1.55, 1.064 and 0.532 µm.
CHAPTER 6
POLYCHROMATIC BEACON DEMONSTRATION EXPERIMENTS

To demonstrate the function of the polychromatic beacon, the integrated system, consisting of the fiber coupling and the beacon collimator sub-systems including the feedback control for the fiber coupling, was set up on one end of a 30m indoor-range hall. The collimated beams were pointed towards the other end of the range hall, where, in 25 meter distance, a lens with a focal length of 30 cm was placed into the beam. This lens focused the beam onto the focal plane array of an infrared camera (SU640SDWH-VIS from Sensors Unlimited) operating with a 256x256 pixel window. The sensitivity range of this NIR camera is enhanced such a way that it is also sensitive for visible light and can be used for the 0.532 µm beam in addition to the two beams in the NIR range. The center of the lens was shifted about 10mm from the beam center. This made it possible, utilizing the dispersion of the lens, to have separate spots in the focal plane for the 0.532 µm and 1.550 µm beams. The dispersion of the lens was not sufficient to separate the spots for 1.064 µm from 1.550 µm, therefore only the wavelengths 0.532 µm and 1.550 µm were used in this experiment. Five meters in front of the lens a single heater was placed directly below the propagating beams to introduce wave front distortions from the artificially generated turbulence. Using this setup, sequences of the irradiance
distribution of the two beams on the camera’s focal plane array were recorded. For the experiment, 1000 frames were captured at a frame rate of 250 Hz, which corresponds to a total recording time of approximately 4 seconds. Samples of frames from the recorded sequence are shown in Figure 45. They show that the focal spots are displaced through the tip and tilt distortions from the turbulence-generating heater. In addition, in many cases the focal spots break up as a result from higher-order wave front distortions across the beam.

![Image of sample frames](image_url)

Figure 45: Sample frames of the recorded sequence of irradiance distribution for 0.532 µm (left) and 1.55 µm (right) in the focal plane after beam propagation over 25 m with a single heater about 5 m in front of the focusing lens.

Using the recorded sequences, the centroid location for the 0.532 µm and 1.55 µm focal spots were calculated for each frame by evaluating following the integrals [28]:

\[
\bar{x}_n = P_n^{-1} \int_{\Omega_n} x I_n(r) d^2r,
\]

\[
\bar{y}_n = P_n^{-1} \int_{\Omega_n} y I_n(r) d^2r,
\]

(30)
Here $I_n(r)$ is the focal plane image captured by the camera, $r = \{x,y\}$ is a two-dimensional coordinate vector, and $n = 1, 2, \ldots, N$. $N$ is the number of the focal plane image (frames) $I_n(r)$ recorded in the sequence of $N = 1000$ frames. $\Omega_n$ is the array area and $P_n$ is proportional to the total power in pixels in the array. For numerical evaluation of these expressions in Equations (30) and (31) the integrals were replaced by sums and the vector $r = \{x,y\}$ was replaced by discrete pixel numbers in $x$ and $y$ directions. The average vectors for the focal spot centroid coordinates (averaged over the entire set of frames in the recorded sequence) are given by

$$\langle \bar{x}_n \rangle_N = \frac{1}{N} \sum_{n=1}^{N} \bar{x}_n \quad \text{and} \quad \langle \bar{y}_n \rangle_N = \frac{1}{N} \sum_{n=1}^{N} \bar{y}_n.$$  \hspace{1cm} (32)

The displacement vectors $\Delta x_n$ and $\Delta y_n$ for the centroid locations are defined relative to the average positions, that is as $\Delta x_n = \bar{x}_n - \langle \bar{x}_n \rangle$ and $\Delta y_n = \bar{y}_n - \langle \bar{y}_n \rangle$. The centroid locations calculated for the experiment with a single heater as turbulence generator are plotted vs. the frame index number $n$ in Figure 46. The correlation coefficient $\rho$ for the centroid position in the $x$ and $y$ axis between the two wavelengths (1.55 and 0.532 $\mu$m) is given by
\[
\rho = \frac{\sum_{n=1}^{N} (x_n - \bar{x}_n)(y_n - \bar{y}_n)}{\sqrt{\sum_{n=1}^{N} (x_n - \bar{x}_n)^2} \sqrt{\sum_{n=1}^{N} (y_n - \bar{y}_n)^2}}
\]  

which is calculated to be 0.8426 and 0.2640 respectively.

Figure 46: Centroid location displacements $\Delta x$ and $\Delta y$ calculated for the $x$ and $y$ axes [(a) and (b), respectively] for the focal spots of two beams with wavelengths 1.55 and 0.532 µm in an experiment with a single heater placed 5 meters from the focusing lens. A value of 5 was added to the data for 1550 nm to better distinguish between the two curves.
In another experiment two heaters were used and placed at distances of 5 and 15 meters from the lens. The calculated curves for the beam centroid displacements are shown in Figure 47. Based on Equation (33) the correlation coefficient $\rho$ between the two wavelengths is calculated to be 0.8554 and 0.7702.

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**Figure 47:** Centroid locations calculated in the $x$ and $y$ axes [(a) and (b), respectively] for the focal spots of two beams with wavelengths 1.55 and 0.532 µm in an experiment with two heaters placed at 5 and 15 meters from the focusing lens. A value of 7 was added to the data for 1550 nm to better distinguish between the two curves.
Based on the results of the centroid calculations shown in Figure 46 and Figure 47, the variances for the focal spot centroid wander in $x$ and $y$ direction were calculated according to

$$
\sigma_x^2 = \frac{1}{N} \sum_{n=1}^{N} (\bar{x}_n - \langle \bar{x}_n \rangle_N)^2 \quad \text{and} \quad \sigma_y^2 = \frac{1}{N} \sum_{n=1}^{N} (\bar{y}_n - \langle \bar{y}_n \rangle_N)^2,
$$

respectively. From these variances (calculated in pixel numbers) the angle of arrival variance $\alpha^2$ (variance of the wave front combined tip and tilt deviation from normal incidence to the focusing lens) can be calculated as

$$
\langle \alpha^2 \rangle = \left( \frac{p}{f} \right)^2 [\sigma_x^2 + \sigma_y^2],
$$

where $p$ is the size of a single pixel of the camera’s photo array (25x25 µm$^2$) and $f$ is the focal length of the focusing lens (30 cm). Using Equation (35) the angle of arrival variance for 1.55 µm and 0.532 µm was calculated to be $3.17 \times 10^{-8}$ rad$^2$ and $1.87 \times 10^{-8}$ rad$^2$, respectively, for the experiment with one heater. Similarly when two heaters were used, $\alpha^2$ was $4.46 \times 10^{-8}$ rad$^2$ and $2.39 \times 10^{-8}$ rad$^2$ for 1.55 µm and 0.532 µm, respectively.

The results presented in Figure 46 and Figure 47 show that there was a generally good correlation between the wander of the focal spots of the beams at 1.55 µm and 0.532 µm as a result of the perfect co-location of the beams upon emerging from the
photonic crystal fiber (PCF). The observed angle-of-arrival fluctuations for 1.55 µm were stronger than those at 0.532 µm.
CHAPTER 7
CONCLUSION AND DISCUSSIONS

This thesis presents the design, experimental setup and results from testing of a polychromatic beacon system with three wavelengths coupled into an endlessly single-mode photonic crystal fiber. The intended use of the polychromatic beacon is in long-distance laser propagation experiments to study and characterize atmospheric effects, such as turbulence and refraction.

A major part of the work was dedicated to the development of a free-space fiber coupling system that combined laser light of three different wavelengths (1.55, 1.064 and 0.532 µm), each from a respective single-mode fiber, in a photonic crystal fiber. Based on an optical design elaborated with ray tracing software (Zemax), a laboratory prototype of the fiber coupling system was developed. The measurements of fiber coupling efficiencies showed that the system was near the theoretical limit at 1.55 µm, and reached about 53% and 74% of the ideal value for 1.064 µm and 0.532 µm, respectively. Discrepancies between measured and predicted values of that magnitude were expected considering the aberrations of optical elements and distortions caused by misalignment of these elements.
The system utilized piezoelectric actuated fiber positioners controlled by SPGD controllers that maximize a performance metric (here fiber coupling efficiency) by lateral movement of the fiber tip of the single-mode fibers in the source collimators. The developed feedback system that uses the power in the tails of the near-Gaussian beams emerging from the photonic crystal fiber to ensure maximum achievable coupling efficiency during system operation even under varying conditions such as temperature changes, or low-frequency vibrations.

The developed prototype system is, in principle, ready for long-range optical propagation experiments. However, a version that occupies less space, that can be better integrated into a gimbal for pointing, and that does not require the use of laboratory-style equipment, such as translation stages for alignment, is desirable. The photonic crystal fiber collimator sub-system can be significantly reduced in size if an apochromatic lens, such as designed in this thesis, is used instead of the off-axis parabolic mirror. The fiber coupling system can be made much more compact, if fiber positioners are mounted into custom-designed fixtures that allow for the use of lenses with considerably shorter focal lengths.
REFERENCES


