Wideband, Scanning Array for Simultaneous Transmit and Receive (STAR)

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

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2017

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Abstract

We present a low profile ($\lambda_{LOW}/8$) wideband slot spiral antenna array with high transmit/receive (Tx/Rx) isolation and beam steering capability for simultaneous transmit and receive (STAR) systems. By suppressing Tx/Rx coupling, this array provides true full-duplex transceivers with wideband scanning capability. STAR increases a channel’s spectral efficiency by transmitting and receiving across the full bandwidth of a channel. To our knowledge, this is the first wideband STAR spiral array with scanning. Each 4-arm spiral element consists of two arms for Tx and two more for Rx. To suppress grating lobes, the element spacing is kept at $\lambda_{HIGH}/2$. Full wave infinite array simulations show the port-to-port Tx/Rx isolation is $>40$dB at boresight across a 3 GHz bandwidth from 2-5GHz (2.5:1). This level of port-to-port isolation reduces to about 30dB when scanning down to 30°. In addition, VSWR is < 2 and axial ratio < 3dB. A 3×3 array prototype was fabricated and tested. Results show an isolation of 36dB (average) across 2-5GHz (min 28dB), which is in full agreement with the simulation. Isolation when scanning remained within 10dB of boresight isolation.
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Chapter 1: Introduction

As available radio frequency (RF) spectrum diminishes and becomes costly, there is growing interest in methods that increase spectral efficiency. Notably, in a 2015 spectrum auction, the Federal Communications Commission (FCC) received over $41 billion in bids for only 65MHz of bandwidth [1]. Simultaneous Transmit and Receive (STAR) allows systems to concurrently transmit as well as receive across the entire bandwidth of the channel and therefore double data capacity [2]. Alternatively, the bandwidth can be reduced by half while maintaining the same data rate. A key challenge with STAR is suppressing transmit/receive (Tx/Rx) coupling. A radio’s transmitter must not interfere with its receiver. Time/frequency domain duplexing (TDD/FDD) methods achieve this by receiving at different times and frequencies than transmitting respectively. Both methods prevent self-interference (SI) at the expense of reduced spectral efficiency. By using a radio with inherent Tx/Rx isolation, the time/frequency restrictions in TDD/FDD become unnecessary. Thus, STAR allows for double the data capacity compared to TDD/FDD systems by concurrently transmitting and receiving across the full channel bandwidth. We must always maintain high isolation between the radio’s Tx/Rx paths to suppress self-interference (SI). As expected, transmitter to receiver coupling lowers the signal to noise plus interference ratio (SINR), reducing communication reliability.
STAR systems overcome SI by one or more of the following techniques: (1) isolated Tx/Rx antennas, (2) RF/analog filters, and (3) digital filters [3]. The antenna stage isolation is a critical piece of high isolation systems, particularly as output power increases. By reducing SI at the antenna ports, the dynamic range of the self-interference decreases to where analog to digital converters (ADC) and digital filtering [4] can provide further cancellation. Thus, realizing STAR systems requires high isolation antennas. We aim to produce high port-to-port isolation over a wide bandwidth (>1GHz) with a scanning array of collocated Tx/Rx elements (See Fig. 1).

Figure 1. A 3×3 array showing an enlarged unit cell with high Tx/Rx isolation
Others have demonstrated STAR, but scanning was only achieved across very narrow bandwidths, such as about 100MHz or less. For example, a patch antenna array used narrowband filters to cancel coupling between adjacent elements across a 110MHz bandwidth when scanning (30dB rejection at boresight) [5]. In addition, wideband STAR was demonstrated from 0.6-2.5GHz, but only for a single element four-arm spiral antenna [6]. A non-scanning array of seven four-arm spirals exhibited 27dB port-to-port isolation across 0.65-2.7GHz [7]. Another method of wideband self-interference cancellation was discussed in [8, 9] using a circular array with progressive phase shifting at the Tx side. In this case, the feeds produced destructive interference at a central Rx element. The design in [8] measured 50dB isolation across 2-2.9GHz. Another variation employed a two-layer circular ring of elements where each Tx/Rx antenna pair were stacked vertically [10]. However, these approaches did not consider scanning.

We introduce a low profile array of four-arm slot spiral antennas for STAR systems. It achieved 36dB Tx/Rx isolation (average) across >3GHz of bandwidth (min 28dB) at boresight and 26dB when scanning to 30°. To our knowledge, this is the first low profile, wideband, beam steering spiral array for STAR. As compared with previous efforts, this array achieves a high port-to-port isolation across GHz bandwidths, also when scanning (>25 times bandwidth increase compared to other works).

To demonstrate a scanning array of STAR spirals, we must overcome several key challenges. First, a miniature spiral element is required with a $\lambda_{\text{HIGH}}/2$ diameter to fit in a
\( \lambda/2 \) spaced array. Many spirals are 1\( \lambda \) or even 2\( \lambda \) in diameter. Clearly, such elements cannot be placed into a scanning array without unacceptable losses due to grating lobes.

![Figure 2. Top-down view (left) and side profile (right) of the four-arm spiral element showing the symmetry between Tx/Rx arm pairs. Two arms are for Tx and the other two are for Rx](image)

Our miniaturized array element is based upon a previously developed single element square spiral [11]. A single termination resistor is placed at the end of each slot arm to reduce reflections, which radiate in the opposite polarization, increasing axial ratio and VSWR. Second, we must maintain symmetry in the spiral arms, baluns, and feeds to ensure high Tx/Rx isolation. In addition to the Tx and Rx coaxial cable feeds, dummy coax feeds were added to maintain symmetry, and therefore isolation (See Fig. 1). Frequency independent isolation is achieved through geometrical symmetry and the orthogonality of the Tx/Rx polarizations [6].
As depicted in Fig. 1 and 2, each spiral element contains two arms for transmission and the other two for reception. Spiral antennas were selected for their excellent circularly polarized (CP) radiation and inherent wideband performance. In applications such as satellite communications, CP polarization is preferred as it minimizes polarization mismatch losses due to unknown antenna orientation or Faraday rotation [12].

We present the design, fabrication, and measurement of a scanning $3 \times 3$ four-arm spiral STAR array. The array achieved 36dB Tx/Rx isolation at boresight, and 26dB when scanning down to $\theta = 30^\circ$. The active VSWR was < 2.2. In Section II, we discuss the design and fabrication of the spiral array as well as the spiral miniaturization for $\lambda_{HIGH}/2$ element spacing. In Section III, we verify the concept with finite array simulations and in Section IV we confirm antenna measurements with scanning, successfully demonstrating the first wideband, scanning STAR spiral array.
Chapter 2: Four-Arm Spiral Antenna Array

The spiral elements and array (See Fig. 2 and 3 respectively) were designed for fabrication on a 2-layer PCB. The slot spiral arms were etched on the lower layer and the feed was placed on the upper layer. Each slot arm was terminated at the outer edge of the spiral by a surface mount resistor placed across the end of the slot arm [11]. The entire array was backed by a ground plane at a distance of approximately $\lambda_{LOW}/8$ as depicted in Fig. 2. A microstrip infinite balun provided the balanced feeding for each Tx and Rx arm pair as well as tapering the impedance up to the 100Ω feed. Thus, no separate balun or transformer was needed behind the antenna, reducing the antenna’s size, weight, and power (SWaP), as well as cost. A 50Ω coax cable through the ground plane fed the microstrip. Ferrite beads were placed around the coaxial cables to reduce parasitic currents on the outer shielding. Notably, each element was miniaturized [11] so that the element-to-element spacing was kept at $\lambda_{HIGH}/2$, ensuring no grating lobes ($f_{HIGH} = 5GHz$). In terms of wavelengths, the diameter of each element was $0.2\lambda_{LOW} = 0.5\lambda_{HIGH}$. Each spiral element was miniaturized with a single termination resistor at the end of each slot arm. This resistor reduced reflections at the end of the slot arms, which lower axial ratio and VSWR. If the scan angle was limited to a specified value, the spiral elements could be further optimized for increased bandwidth and gain while avoiding grating lobes.
Figure 3. A $3 \times 3$ array showing the half-wavelength element spacing (at 5GHz). The inset in the lower right corner is a side view showing the PCB’s layer stackup and coaxial feeding.

The four-arm spiral relies on physical symmetry to produce high isolation. Thus, creating a symmetric spiral and balun are of great importance, especially at the upper frequencies of an antenna’s bandwidth where dimensions are electrically larger. A common balun for two-arm spirals is the infinite balun, which can be replicated for four-arm spirals. Each four-arm spiral will have two single-ended feeds. In the STAR four-arm spiral, one port is for Tx and the other port is for Rx. The resulting four-arm spiral infinite balun on a two-layer board is physically impossible due to the overlap at the center of the spiral. Previously, four-arm spirals that were fabricated on two-layer PCBs usually used an
offset via to cross under (See Fig. 4). However, achieving high isolation at 5GHz required a more symmetric balun. Placing a 0Ω jumper across the top of the center of the spiral allowed the feed to be placed on one layer on the PCB. Simulations showed the higher symmetry improves the minimum isolation by >7dB. The authors also investigated three-layer designs where each balun’s microstrip trace was placed on a separate layer, thus no crossover was required. However, this produced high isolation only at lower frequencies in the bandwidth. The new cross-over configuration enables fabrication of STAR spiral arrays with PCB techniques at higher frequencies.

Figure 4. New feed design with >7dB increased Tx/Rx isolation as compared with previous designs (upper right picture). Isolation improves because we increased the symmetry at the center of the spiral feed. Notice how the older design (lower right) cuts into one of the spiral arms.
Chapter 3: Infinite and Finite Array Simulations Confirm High Isolation

Full wave simulations of an infinite array confirmed that the spirals achieved a high port-to-port isolation of >40 dB from 1-5 GHz (5:1 bandwidth) at boresight, as shown in Fig. 5. At frequencies lower than about 3GHz (1.9GHz bandwidth), the isolation exceeded the 50 dB level. When scanning down to θ=30°, the isolation remained >30dB from 2-5GHz (2.5:1). The active VSWR was < 2 (See Fig. 6) with a corresponding axial ratio of < 3dB across the entire bandwidth (2-5GHz), even when scanning.

![Port-to-Port Coupling While Scanning θ](image)

Figure 5. Unit cell in an infinite array shows >40 dB Tx/Rx port-to-port isolation at boresight and 30dB when scanning down to 30° across 2-5GHz
Figure 6. Even when scanning to $30^\circ$, the active VSWR in an infinite array unit cell was $< 2$ across 2-5GHz

A 3×3 finite array simulation produced similar results to the infinite array. The minimum port-to-port isolation was 40dB, also with excellent matching and axial ratio $< 3$dB (See Fig. 7). Scanned gain patterns show side lobe levels $> 10$dB below the main lobes (See
Fig. 8). A 3x3 array was selected instead of a 5x5 or larger array to compare prototype measurements with simulations.

![3x3 Array Pattern While Scanning (5GHz)](image)

Figure 8. Realized gain pattern of 3×3 array shows minimal loss and low side lobe levels (>10dB below co-pol) when scanning down to 30° (simulated)

Full wave simulation sweeps of manufacturing tolerances (±10%) showed that excellent isolation performance was possible with standard PCB fabrication techniques and 5 mil feature sizes. Finer minimum dimensions could result in better matching and higher isolation.
Chapter 4: Measurement Results for Scanning STAR Array Verification

Measurements confirmed the simulations and showed 36dB Tx/Rx isolation (average), as shown in Fig 9-10. When scanning down to θ=30°, the isolation deteriorates by <10dB compared with boresight isolation across 2-5GHz. At some frequencies the isolation improved by 7dB. The active VSWR when scanning remained < 2.2 across the entire bandwidth, as shown in Fig 11-12. A picture of the fabricated 3x3 array is shown in Fig. 13 and 14.

![3x3 Array Tx/Rx Coupling at Boresight](image)

**Figure 9.** Measured Tx/Rx coupling reached 36dB (average) with a minimum value of 28dB across 2-5GHz
Figure 10. When scanning down to 30°, the isolation deteriorates by <10dB and even improves by 7dB at some frequencies compared with boresight isolation.

Figure 11. Measured active VSWR shows excellent agreement with simulations.
Figure 12. The active VSWR remains < 2.2 across 2-5GHz when scanning down to 30°

Figure 13. Picture of the fabricated STAR spiral array. The feeds are visible on the top PCB layer
Figure 14. Photo of the printed circuit board’s lower layer showing the slot spiral arms with assembled connectors and resistors
Chapter 5: Conclusion

A wideband scanning array of spiral antennas with high port-to-port isolation and beam steering capability was designed for STAR systems. STAR allows radios to concurrently transmit and receive over the entire channel’s bandwidth, increasing data capacity. Antennas with highly isolated Tx/Rx ports provide a significant step in achieving the isolation necessary for true full-duplex operation.
References


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