Broadband Near-field Filters for Simultaneous Transmit and Receive in a Small Two-Dimensional Array

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***Abstract*—In order to enable Simultaneous Transmit and Receive (STAR), it is essential to provide high isolation between antenna elements. A novel technique is presented here in which tunable resonators are used in the near-field of an array of antennas to provide transmission zeros in the coupling between antennas. By using two sets of tunable resonators between each set of adjacent antennas, it is possible to significantly increase the bandwidth of the isolation provided relative to previous topologies used to give isolation between planar antennas.**

***Index Terms*—Antenna Arrays, Simultaneous Transmit and Receive, Tunable filters.**

I. Introduction

Multifunction digital back-ends allow modern arrays to perform more tasks with more flexibility than previous fixed-purpose analog arrays. In order to make the most efficient use of a multifunction array it is desirable to create a system capable of simultaneously transmitting and receiving. The fundamental challenge that must be overcome in order to enable simultaneous transmit and receive (STAR) in an array is to prevent the transmitters from self-jamming the receiver. In many systems, over 100 dB of isolation is required between transmitters and receivers in order to reduce transmit-receive coupling below the noise floor. Some of this isolation can be achieved through the use of active RF and IF cancellers. These cancellers must be highly linear in order to fully cancel the transmitted signal on the receive path. Thus it is essential to provide some measure of isolation between the transmit path before the cancelers. Depending on the system, the required transmit-receive isolation before the RF cancellation stage can range from 20 to 40 dB.

If the transmitted signal is at a different frequency than the receive signal, a diplexer can be used to provide the isolation required between transmitters and receivers. However, if the transmitted signal is at the same frequency as the desired receive signals, such as in a radar system, a diplexer cannot be used and isolation must be achieved through some frequency independent means.

There are two classes of antenna arrays designed for STAR; those that use the same elements for transmit and receive, and those that use separate elements for transmit and receive. In the latter case, isolation can be provided through cancellation schemes [1]. This cancellation can even be made tunable in order to allow full freedom in beam-steering [2]. However, these schemes either limit the possible scan range of the array, or require retuning for each new transmit scan angle to account for phase and amplitude changes of the transmitters.

In the scenario in which every element is used to both transmit and receive, a circulator or circulator-like device must be used to provide transmit-receive isolation. Individual circulators have been demonstrated to provide as much as 40 dB of isolation [3], which is sufficient for the first step of isolation provided in a STAR capable system. However, these circulators assume the antenna will provide a 50 Ω load. In actuality, the effective impedance of an antenna element in an array changes with respect to scan angle, due to the coupling between antenna elements, as shown in (1). Any reflection seen at the antenna will feed the transmitted signal directly through the circulator to the receiver.

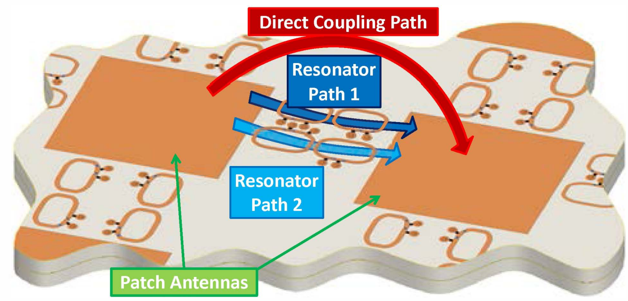

Fig. 1. Coupling paths through and around near-field filters.

$$S_{11,active} = S_{11} + \sum_{n=2}^{N} A_n S_{1n} \tag{1}$$

A simpler approach is to provide direct isolation through near-field filtering techniques. This is accomplished by placing resonators in between the radiating antennas of an array such that they provide direct isolation between the antenna elements, as demonstrated in reduction of H-plane coupling in [4]. These techniques provide high isolation that in some cases can even be tuned in frequency. However, the bandwidth of the isolation is typically limited due to the absorptive band-stop topology used to achieve high isolation.

A novel approach is presented here in which multiple paths of coupling between each antenna allow tunable isolation to be provided across much broader bandwidths than previous near-field filters [4]. This design is made possible through the use of varactor-tuned split-ring resonators, which provide enough coupling to the patches and each other in both the E and H planes while fitting in between patches spaced a half wavelength apart. Isolation bandwidths of 110 MHz at 30 dB and 55 MHz at 40 dB have been demonstrated and are shown below.

Real(M)	UP1	R1	R2	R3	R4	UP2
Upper Patch 1	-1.32	1.46	0.56	1.58	0.67	-0.78
Resonator 1	1.46	-3.56	-1.28	-0.23	-0.50	0.57
Resonator 2	0.56	-1.28	4.41	-0.17	-0.68	1.36
Resonator 3	1.58	-0.23	-0.17	0.43	-2.13	0.67
Resonator 4	0.67	-0.50	-0.68	-2.13	-0.20	1.57
Upper Patch 2	-0.78	0.57	1.36	0.67	1.57	-1.14

Self-Coupling terms | Direct Coupling | Path 1 | Path 2

Fig. 2. Extracted coupling matrix M of a 1-by-2 antenna array with two paths of resonators.

II. Near-Field Filtering

In order to effectively model the resonators placed between antenna elements in an array, it is useful to use microwave filter theory. Specifically, by using coupling matrix theory [5], the couplings between the resonators used in the near-field filter and the antennas can be evaluated and adjusted to provide maximum isolation.

In this work, two parallel paths of resonators are used to enable transmission zeros, as shown in Fig. 1. By placing these zeros close to one another in frequency, the bandwidth of the isolation can be significantly improved over the bandwidth available using only one transmission zero.

In order to provide two independent coupling paths through the tunable resonators, varactor-tuned split-ring resonators were used. These resonators are small enough to enable the placement of two independent paths of resonators between a set of patch antennas while maintaining enough coupling between the resonators and the patches. The coupling between these resonators and their neighbors is highly dependent on the orientation of the varactor-tuned gap. Thus, by choosing this gap placement carefully, large amounts of coupling can be achieved in-line with the chosen coupling path, while the parallel paths have relatively low cross-coupling.

A. Coupling Matrix Extraction

The coupling matrix containing the coupling coefficients relating each of the resonators in the antenna-filter system can be extracted through the use of the technique demonstrated in [6] and [4]. This requires an EM simulation of the antenna filter system with at least one port on each resonator. The resulting admittance matrix Y can then be used to mathematically derive the coupling coefficients between each resonator in the system. This coupling matrix can then be used to determine which couplings are too weak or too strong, allowing the designer to ensure that transmission zeros can be placed at the desired frequencies.

Fig. 2 shows the real part of the extracted coupling matrix of two adjacent patch antennas with two paths of tunable intermediate resonators consisting of two resonators per path. It can be seen from this that the coupling coefficients through the resonators are significantly stronger than the direct near-field coupling from one patch to the other. This is important, as there is non-negligible loss in the tunable resonators due to the varactor loss.

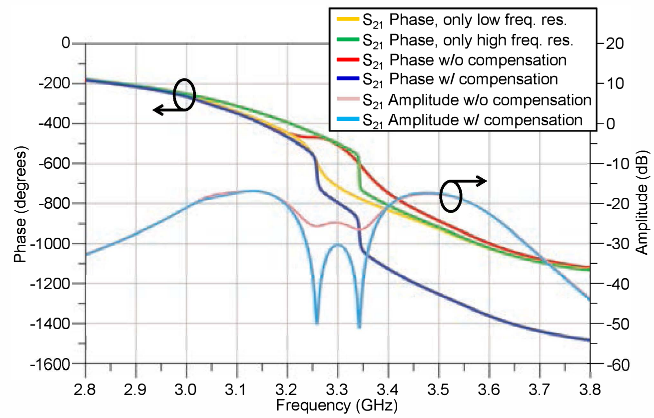

Fig. 3. The phase and corresponding amplitude of S_{21} with and without compensation for proximity of the resonances.

III. Results

A. Filter Tuning

In order to achieve a zero in the pass-band of the near-field filter, the amplitude of the energy coupled through the tunable resonator path must be equal in magnitude to the energy coupled directly from the source to load. In a system with two over-coupled tunable resonators this can be achieved by tuning one slightly higher in frequency than the desired frequency for the zero and the other lower in frequency. This results in a lower effective coupling, which allows the resonator path to be balanced with the direct path.

When two paths of two resonators are used to broaden the bandwidth, the interaction between the two paths requires the path being used for the higher frequency zero to be detuned further. This enables the energy coupled through both paths of resonators to cancel the direct path, giving a broader bandwidth of isolation. The closer the two zeros are placed, the more the higher frequency zero must be detuned, as demonstrated in Fig. 3. However, when the two resonators are too far detuned, they stop working in tandem and are essentially two independent resonators. At this point, there is no way to reduce the coupling through the resonators by detuning them. As such, this places an effective limit on how close the zeros can be brought to each other. This also means there is a limit on the maximum depth of achievable isolation with the two paths of cancellation. If greater depth of isolation is required, one of the sets of resonators can be tuned to an unused frequency to allow the other set to be tuned for maximum isolation.

B. Measurements

Two small arrays were built and measured. The first was a 1x2 H-plane array, and the second was a 2x2 array with near-field filters in both the E and the H planes. Fig. 4 shows simulated and measured antenna-to-antenna isolation through

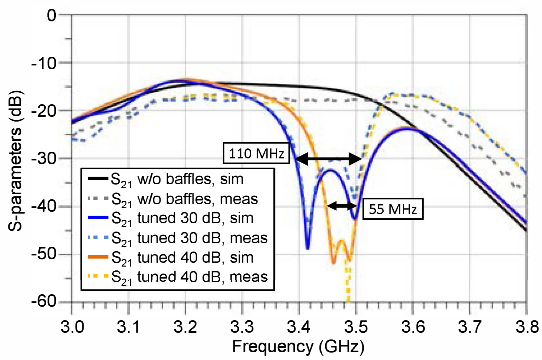

Fig. 4. Measured and simulated inter-element coupling with and without near-field filters in a 1x2 array

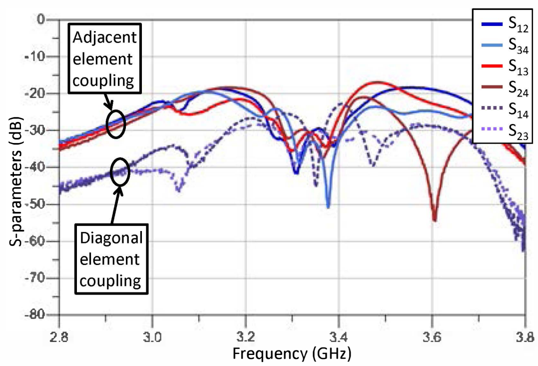

Fig. 5. Measured inter-element coupling in 2x2 array with near-field filters tuned to provide 30 dB isolation between adjacent elements

the 1x2 array for various tunings of the near-field filters, and demonstrates the ability to reconfigure the near-field filters to trade off bandwidth and isolation.

Fig. 5 shows the measured coupling in the 2x2 array when tuned to provide 30 dB of isolation between adjacent elements. The diagonal coupling between elements one and four actually becomes the limiting factor in regards to bandwidth of isolation. This could possibly be corrected by placing near-field filters along the diagonals of the array.

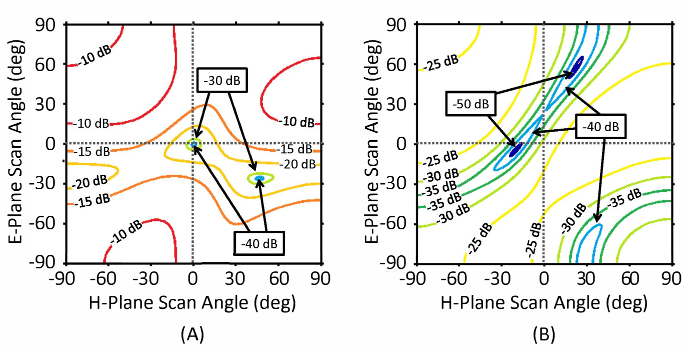

Fig. 6. Active scan reflection of one element in 2x2 array without (A) and with (B) tunable near-field filters using measured S-parameters and simulated fixed capacitive matching network

In order to show the applicability of the near-field filters to STAR at every frequency, the effect of the coupling on the active reflection was considered for multiple scan angles. A simulated matching network consisting of a varactor shunting the antenna's 50 ohm feed to ground one-third of a wavelength from the antenna feed was used to match the antenna's impedance at broadside. Using the same varactors used to tune the baffles, the simulation indicated that this matching network added around 0.175 dB of loss. Fig. 6 shows the active reflection with and without the tunable near-field filters. These reflection coefficients are plotted for the phase-weights that would produce scan angles from -90 to 90 degrees given isotropic radiating elements. Since the measured array is small, the element radiation patterns will limit the achievable scan angles. However, Fig. 6 indicates that the near-field filters keep the active scan impedance is within a much tighter tolerance, allowing over 20 dB of isolation through an adequate circulator.

IV. Conclusion

Tunable near-field filters have been demonstrated herein to provide reconfigurable bandwidth and depth of isolation between adjacent elements in both the E and H planes. This isolation provided is a key enabler of STAR, and the bandwidths achieved are relevant for both communication and radar signals. The ability to retune the filters to provide varying depths of isolation would enable multifunction arrays to be reconfigured to achieve the maximum possible isolation for a given transmitted signal bandwidth, while the frequency reconfigurability of the array ensures that the isolation could be placed wherever it is needed. In addition, this technique can reduce the active reflection of an array to better than -20 dB across all scan angles, enabling circulators to provide over 20 dB of isolation for arrays where every element is simultaneously transmitting and receiving.

References

[1] T. Snow, C. Fulton, and W. Chappell, "Transmit receive duplexing using digital beamforming system to cancel self-interference," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 59, no. 12, pp. 3494 –3503, dec. 2011.

[2] A. T. Wegener and W. J. Chappell, "Simultaneous transmit and receive with a small planar array," in *Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International*, June 2012, pp. 1 –3.

[3] C. H. Cox and E. I. Ackerman, "Photonics for simultaneous transmit and receive," in *Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International*, June 2011, pp. 1 –4.

[4] A. T. Wegener and W. J. Chappell, "Coupled antenna scheme using filter design techniques and tunable resonators to show simultaneous transmit and receive," in *Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International*, June 2013, pp. 1–4.

[5] R. J. Cameron, "Advanced filter synthesis," *Microwave Magazine, IEEE*, vol. 12, no. 6, pp. 42–61, October.

[6] X. Yin, "Accurate extraction of coupling matrix for coupled resonator filters," in *Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International*, june 2012, pp. 1 –3.