

Removal of Beam Squint in Series Fed Array Antennas Using Abnormal Group Delay Phase Shifters

Introduction

Phase shifting networks are ubiquitous in microwave devices and applications such as antenna feed networks where precise phase shifters are necessary for radiation pattern synthesis. Ideally, a phase shifter must provide low insertion loss, good matching, and achieve the desired phase shift over the required bandwidth. For a phase shifter with an approximately linear phase response, the phase bandwidth – the frequency range over which the phase error is within a given tolerance – is inversely proportional to the group delay [1]. Therefore, a phase shifter optimized for maximal phase bandwidth should ideally exhibit zero group delay. To achieve some of the above goals designers often periodically load a matched host transmission line (TL) with lumped elements to synthesize new dispersive properties [2-3]. For example, a microstrip TL is loaded with surface-mount components to construct 2-port networks exhibiting negative group delay (NGD) [2] and negative phase delay [3].

In this paper, the concept of beam squint in series-fed linear array antennas is discussed. A new unit cell with both zero group delay and zero phase delay is proposed. Moreover, a Negative Refractive Index (NRI) TL such as those described in [3] are additionally loaded with lossy resonators to provide the desired NGD, thereby compensating the positive group delay of the initial NRI-TL. Such TL when used as inter-element phase shifter in a series-fed linear array antenna will greatly reduce the beam squint.

Series-fed Antenna Array Phase Shifters

Consider a series-fed linear antenna array shown in figure 1. The antennas are physically spaced a distance d_E apart and are connected through a phase shifter of phase shift ϕ_0 . The array antenna's main beam angle θ , determined using the array factor, is given by (1) provided that the antenna elements are sufficiently close such that the visible region does not capture two main lobes. The beam angle is a periodic function of the inter-connecting phase shift (ϕ_0) and free-space propagation constant (k_0). It is important to note that the value of m (an integer) indicates which maxima of the array factor is captured by the visible region of the antenna producing a main lobe. The value of m must be selected such that the magnitude of the arcsine argument in (1) remains less than or equal to one, otherwise no discernable main lobe exists.

$$\theta(\omega) = \sin^{-1} \left(\frac{\phi_0 + 2m\pi}{k_0 d_E} \right) \quad (1)$$

Variations of the beam angle (θ) with frequency – the so called beam squint – is mathematically quantified by the derivative of the beam angle with respect to frequency [(see (2))]. For non-scanning applications, beam squinting should be minimized to allow a

wider bandwidth of operation. Based on (2), the minimization of beam squint is accomplished by allowing the visible region to capture the array factor's local maximum at $\phi_0=0$, thereby allowing $m=0$ and by ensuring that the phase delay (τ_p) and group delay (τ_g) are equal. However, for conventional TLs the condition in (1) cannot be satisfied unless the TL is extended requiring $m > 0$. This comes at the expense of increased area of the phase shifting network and more importantly, at the cost of reduced operational bandwidth and increased beam squint. Beam squint as defined in (2) can be removed entirely by ensuring: i) $m=0$, and ii) phase and group delays are equal to one another. This implies the need for a phase shifter exhibiting abnormal group delay (i.e. superluminal or negative group delay.)

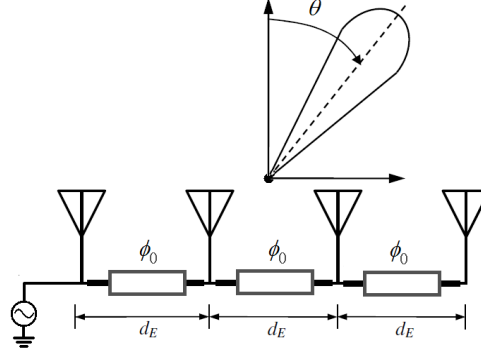


Figure 1: Series-fed linear array antenna topology with TL feed network

$$\frac{\partial \theta}{\partial \omega} = \frac{\frac{\partial \phi_0}{\partial \omega} - \frac{\phi_0}{\omega} - \frac{2m\pi}{\omega}}{\sqrt{(k_0 d_E)^2 - (\phi_0 + 2m\pi)^2}} = - \frac{\tau_g - \tau_p - \frac{2m\pi}{\omega}}{\sqrt{(k_0 d_E)^2 - (\phi_0 + 2m\pi)^2}} \quad (2)$$

To address this problem, some authors have suggested the use of an NRI-TL [4] – a matched low loss TL network exhibiting negative phase delay. The NRI-TL's negative phase delay property allows it to satisfy (1) with $m=0$. As a result, the beam squint may also be reduced, however it cannot be eliminated. The complete removal of beam squint or even direction change requires the addition of abnormal group delay. A NRI-TL does not necessarily produce less beam squint than its non-loaded TL counterpart. By comparing the beam squint calculated in (2) of both the NRI-TL and non-loaded TL phase shifters, the inequality condition shown in (3) indicates which TL produces less beam squint. In order to reduce beam squint for a particular antenna element spacing, beam angle, and substrate relative dielectric permittivity ϵ_r , an NRI-TL phase shifter is recommended when the inequality given in (3) is satisfied.

$$\frac{\lambda}{2d_E} > \sqrt{\epsilon_r} - \sin \theta \quad (3)$$

If this inequality condition is not satisfied, then a conventional unloaded TL should be used or if space is an issue, a TL maybe low-pass loaded to increase the TL's effective phase delay thereby requiring a shorter length.

NRI/NGD-TL Phase Shifter Design

The beam squint formula in (2) indicates that if the phase and group delays are equal and $m=0$, the beam squint can be eliminated. This requires a TL structure with abnormal group delay; i.e. a negative or superluminal group delay. It was shown in [1] that a TL could be loaded with lossy resonators to achieve NGD. In fact, the NRI-TL can also be loaded in a similar manner to achieve both NGD and NRI, simultaneously. Here, we have proposed a NRI-NGD TL phase shifter. The unit cell of our proposed NRI-NGD TL phase shifter is shown in Figure 2. Although this unit cell is non-symmetric, correct usage of the broadband matching condition in [1] can maintain good return losses for both ports. The two components denoted by the nri subscript produce the required negative phase delay and the resonators produce the required NGD. The four TL sections in figure 2 represent the host TL. The innermost TL sections represent the TL section where the surface-mount component pads are connected and its length should be minimized.

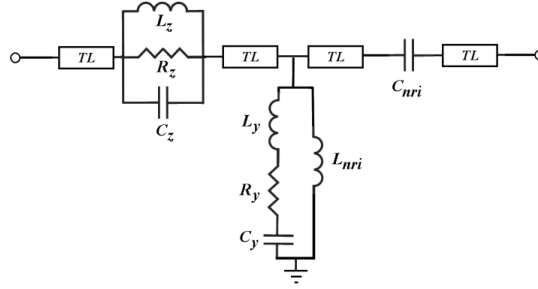


Figure 2: NRI-NGD TL Phase Shifter Unit Cell

Two phase shifters with 0° phase shift – and thus zero phase delay – spanning a port-to-port distance of 10mm, operating at 1GHz, are designed and simulated for comparison. To minimize beam squint, the group delay should be equal to the phase delay and thus be zero. Both phase shifters include 0603 Murata surface-mount capacitors and 0603 Coilcraft surface-mount inductors and use a Rogers RT Duroid 5880 substrate with relative dielectric permittivity $\epsilon_r=2.2$ and height $h=0.787\text{mm}$. These surface-mount components are non-ideal and vary with frequency so for the design to be accurate and produce the required zero group delay over a wideband, Modelithics' passive component models in Agilent ADS software are used. These models take into account the substrate and pad dimensions used and allow for optimization techniques, thereby increasing accuracy. We have used optimization techniques, considering only physically available surface-mount components in our design and obtained return losses of 13 dB or more.

The first device is an NRI-TL phase shifter designed using 3 surface-mount components in a symmetric T-configuration similar to [3] with $L_{nri}=150\text{nH}$ and $C_{nri}=33\text{pF}$. The second is the NRI-NGD TL phase shifter shown in Figure 2 and its component values are given by: $R_y=100\Omega$, $R_z=15\Omega$, $L_y=121\text{nH}$, $L_z=6.2\text{nH}$, $L_{nri}=51.1\text{nH}$, $C_z=12\text{pF}$, $C_y=0.75\text{pF}$ and $C_{nri}=27\text{pF}$. The phase response versus frequency is shown in figure 3. The $\pm 2^\circ$ phase bandwidths of the NRI-TL and NRI-NGD TL phase shifters are 79 MHz and 553 MHz, respectively. This represents a 7-fold improvement in bandwidth. Both phase shifters have minimum return losses of 13dB over the frequency range from 0.6 GHz to 1.2 GHz. The NRI-TL has an approximately constant insertion loss of 0.13dB, whereas the NRI-NGD TL has an insertion loss of 2.6dB with a 0.05dB ripple from approximately 0.8GHz to 1.1GHz. This small gain ripple over a wideband is attributed to multiple resonances, characteristic of parasitic effects resulting from surface mount components.

The main beam angles given by (1), using the phase shifts produce by the two simulated phase shifters in addition to a meandered TL, are shown in figure 4. The beam angle for the NRI-NGD TL phase shifter is evidently far flatter than its counterparts. The bandwidths over which the main beam angle remains within $\pm 5^\circ$ for the conventional TL, NRI-TL, and NRI NGD-TL are given by 27MHz, 122MHz and 607MHz, respectively. Therefore, the NGD provides a 5-fold improvement for this figure of merit. In order to maintain antenna efficiency and gain, the addition of power amplification is advised to compensate the insertion loss coupled with NGD and, if it is desirable, to control the antenna elements' excitation magnitude for a tailored radiation pattern.

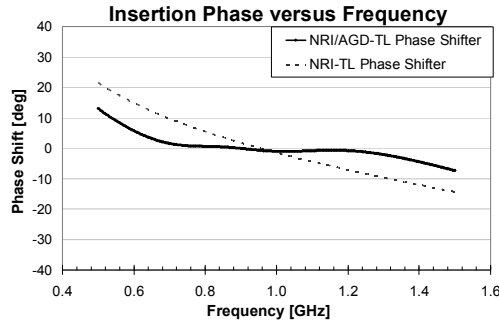


Figure 3: Simulated Phase Response versus Frequency for 0° Phase shifters

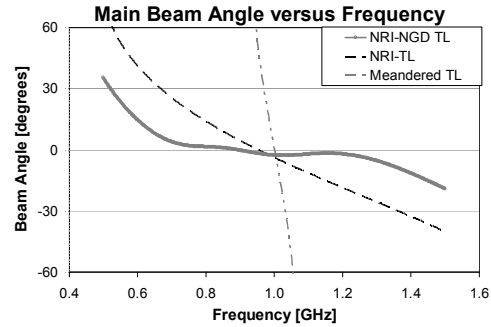


Figure 4: Main Beam Angle vs. Frequency

Conclusion

A series-fed linear array antenna requires inter-element phase shifters with reduced group delay in order to minimize the beam squinting. The selection between a NRI-TL or a non-loaded TL for planar phase shifters for reduced beam squinting depends on the beam angle and inter-element spacing. Both methods can have NGD added via lossy resonators to remove beam squint. A NRI-TL with added NGD is demonstrated leading to a 7-fold increase in phase bandwidth over its non-NGD counterpart. The $\pm 5^\circ$ beamwidth is increased 5-fold by the addition of NGD, with an addition of 2.47dB insertion loss.

References

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