Squint-Free Leaky-Wave Radiation with Non-Foster Artificial Transmission Lines

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Abstract

A periodic structure is presented in which a microstrip transmission line (TL) is loaded with non-Foster negative capacitors. This loading decreases the effective capacitance of the host TL and makes it fast; thereby, the resulting artificial TL supports leaky waves. The main attribute of the proposed leaky-wave antenna (LWA) is that the beam direction remains effectively unchanged over a broad frequency range. This is in contrast to traditional passive LWAs which suffer from beam-squinting. This novel type of a LWA can be used in systems which need the high-directivity, simple feeding and broad impedance bandwidth offered by LWAs, while enjoying a unique squint-free operation.

1. Introduction

Leaky-wave antennas, in addition to being associated with some interesting electromagnetic phenomena, are also attractive from the practical point of view. These antennas are well known for their broad impedance bandwidth, high directivity, simple feeding network and frequency beam scanning [1]. Beam scanning (squinting) means that the direction of the main beam is not fixed with frequency and scans the space within some angular range between the backfire and endfire directions. Although this latter property can be exploited for some specific applications (for example finding an appropriate frequency channel in a multi-path environment), for many applications it is considered undesirable (for example when trying to direct an ultra-broadband signal at a specific direction). For this reason, different researchers have tried to come up with solutions by which the beam squinting can be reduced (e.g. see [2]).

In this paper, we present a LWA in which the beam-squinting can be effectively eliminated over a broad frequency range. The structure comprises a regular non-dispersive TL periodically loaded with negative capacitors. Negative capacitors can be implemented using active circuits called negative-impedance-converters (NICs) [3]. Negative capacitors (and also negative inductors) are referred to as non-Foster components, because, they do not obey the Foster's reactance theorem for passive two-terminal devices.

2. Theory and Design

LWAs belong to the family of traveling-wave antennas. In a LWA, the wave propagating along a guided-wave structure with a phase constant constant β continuously leaks out into free space with a small leakage factor α. The condition for leakage is that the phase velocity, $v_p = \omega/\beta$, in the guiding structure would be greater than the speed of light, c, in free space (i.e. $v_p > c$; or equivalently, $\beta < k_0$; $k_0 = \omega\sqrt{\mu_0\epsilon_0}$ being the phase constant in free space) [1]. This condition suggests that the dispersion diagram (ω-β diagram) can be divided into fast and slow regions, as shown in Fig. 1.a. The leaky wave radiation

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is associated with the structures for which the dispersion diagram lies in the fast region. For a LWA, the angle of the main beam, θ_m, with respect to the broadside, is obtained from [1]:

$$\theta_m = \sin^{-1}(c/v_p) = \sin^{-1}(\beta/k_0) \quad (1)$$

Conventional LWAs are highly dispersive. As an example, the dispersion diagram of a negative-refractive-index TL (NRI-TL) with a closed stopband which can be used as a LWA is shown in Fig. 1.a [4]. In view of (1), when a NRI-TL is employed as a LWA, the main beam can ideally scan the space from the backfire to the endfire direction through broadside. As depicted in Fig. 1.a, for creating a LWA without frequency beam-scanning, the dispersion diagram, in addition to being in the fast region, should be linear and pass through the origin. In other words, the structure should be fast and non-dispersive. Such a structure can be implemented using non-Foster negative capacitors.

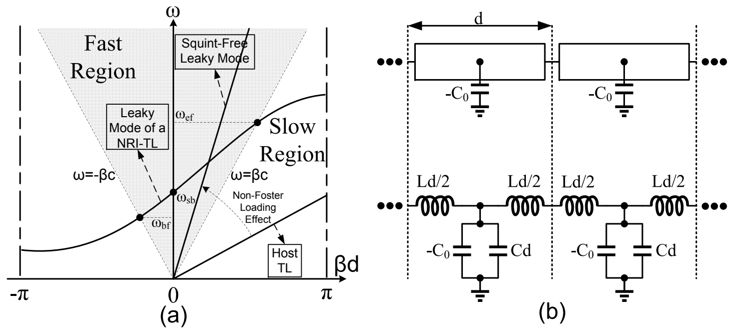


Fig. 1: (a) The fast and slow regions in dispersion diagram with examples of dispersive and non-dispersive leaky modes. (b) A TL is made fast by periodically loading with negative capacitors.

Consider a host 1-D non-dispersive TL which is open to free space and is periodically loaded with non-Foster negative capacitors as shown in Fig. 1.b. The host TL is slow and its characteristic impedance and propagation constant are obtained from $Z_{host} = \sqrt{L/C}$ and $\beta_{host} = \omega\sqrt{LC}$ respectively, where $L(H/m)$ and $C(F/m)$ are the per-unit-length inductance and capacitance of the host TL [5]. Turning our attention to the loaded line in Fig. 1.b, we assume that the effective medium approximation holds for this periodic structure; that is $d << \lambda$ in Fig. 1.b. Hence, the characteristic impedance and phase constant of the loaded TL are:

$$Z_{loaded} \approx \sqrt{\frac{L}{C - C_0/d}} \quad ; \quad \beta_{loaded} \approx \omega\sqrt{L\,(C - C_0/d)} \quad (2)$$

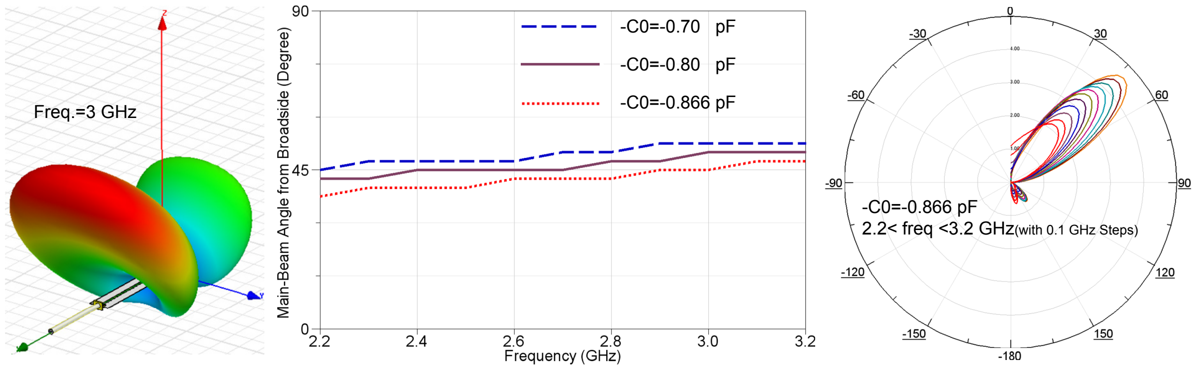
This equation indicates that non-Foster loading tends to decrease the phase constant of the host TL and make it fast while preserving its non-dispersive nature. The parameters of the host TL are selected such that Z_{loaded} would be matched to the characteristic impedance of the system Z_0.

The design begins with selecting the unit-cell size d to maintain the effective medium approximation at the maximum frequency of operation. Subsequently, by selecting the main-beam angle θ_m and enforcing the matching condition for the loaded TL, it can be shown that Z_{host} and C_0, for a host medium with effective dielectric constant ϵ_{eff}, satisfy the following equations:

$$Z_{host} = \frac{Z_0 \sin\theta_m}{\sqrt{\epsilon_{eff}}} \quad ; \quad \frac{C_0}{d} = \frac{\epsilon_{eff}}{c\, Z_0 \sin\theta_m}\left(1 - \frac{\sin^2\theta_m}{\epsilon_{eff}}\right) \quad (3)$$

3. Simulation Results

A LWA of the proposed kind is designed using a 20 mil, RO4003 substrate (from Rogers Crop.) with a dielectric constant equal to 3.38. For this substrate $\epsilon_{eff} \approx 3\epsilon_0$. The unit-cell is made in microstrip and its size is selected to be d=5 mm. The width of the microstrip line is 3 mm. A LWA composed of 20 unit cells is simulated using HFSS for different values of non-Foster loading capacitors. The structure along with the 3D radiation pattern result at $f = 3$ GHz are shown in Fig. 2.a. The 3-D pattern is similar to the form that we expect from a 1-D LWA. To check the beam-squinting behavior, the antenna is simulated over a broad frequency range from 2.2 to 3.2 GHz and the direction of the main beam vs. frequency is plotted in Fig. 2.b for three different values of loading elements. As shown, the angle of the main beam with respect to the broadside decreases as one increases the amount of negative loading, but, for a constant value of the loading element, the direction of the main beam changes within a small limit over a broad frequency range. This can be further verified in the 2-D pattern drawn for a certain value of the loading element in Fig. 2.c. These results show that the beam-squinting in conventional passive LWAs can be significantly decreased using this method. The deviation from the ideal no-beam-squinting behavior is due to the discreteness of the structure.



(a) (b) (c)

Fig. 2: (a) LWA and 3-D radiation pattern. (b) Angle of the main beam vs. frequency for the TL loaded with different values of non-Foster capacitor. (c) 2-D Radiation pattern in the $\varphi = 0$ cut.

4. Conclusion

A squint-free LWA antenna has been proposed in this paper. The leaky-wave radiation in this antenna is obtained by periodically loading a host TL with non-Foster negative capacitors. This type of loading, while making the antenna fast, preserves the non-dispersive nature of the host TL, thus, the beam-squinting can be effectively eliminated over a broad frequency range. Theory and supporting simulation results have been presented.

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