Nonreciprocal and Magnetically Scanned Leaky-wave Antenna Using Coupled CRLH Lines

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Abstract— A new class of magnetoelectrics-based leaky-wave antennas (LWA) is proposed for wide angle beam-steering via magnetic tuning. This new LWA is based on coupled composite-right-handed microstrip lines printed on a ferrite substrate. To accomplish radiation, the printed coupled transmission lines are operated in the fast wave region (|β|<k₀). Beam-steering was attained by changing the magnetic properties of the ferrite, controlled by the external bias field. Specifically, the beam was successfully scanned in the E-plane by 80° via changing the bias field by ±500Oe. The associated gain varies between 3.5dB and 5dB at the operating frequency 1.85 GHz as the beam is scanned.

I. INTRODUCTION

There is a strong interest in cost-effective, low profile, high gain, scanning antennas for high bandwidth satellite communication. To date, antenna beam steering was done by electronically scanned phased arrays or by leaky-wave antennas that support fast-waves. In the first case, high cost and bulkiness are inevitable due to necessary phase shifters and feeds at each element. For the latter, scanning range is limited and LWAs are several wavelengths long as they do not incorporate slow wave techniques. Further, most of the designs employ frequency modulation to achieve beam steering, implying additional challenges for RF sources and large bandwidth designs [1]. To alleviate this issue, ferrites have been incorporated in LWAs to realize continuous scanning with bulky electromagnets [2]. Clearly, this approach is not practical for low-profile, light-weight antennas required in small vehicles. In this effort, a new class of magnetoelectrics-based leaky-wave antennas (LWA) is proposed for wide angle beam-steering via electrical tuning. Proposed LWA is depicted in Figure 1 and is formed by a pair of coupled transmission lines printed on a magnetoelectric (ME) composite film, where ferrite and piezoelectric ceramic layers are coupled through mechanical interaction. That is, the voltage VDC applied to the piezo layer introduces a mechanical deformation (expansion of the piezo surface) to change the magnetic field inside the ferrite layer (H₀) due to the magnetostrictive strain at the interface. As such, the magnetic properties of the ferrite (controlled by H₀) can be tuned by varying VDC in the piezoelectric layer to achieve beam-steering. High ME coupling coefficients (required for wide angle scanning with a small VDC) have been reported for several μm thick YIG and PZT composites [3]. The fabrication of these μm thin films is very challenging and corresponding ME coefficients (Oe·cm/kV) depend on the interfacial bonding quality, sample thicknesses and strength of the applied voltage. Incorporation of composite sample properties in the LWA design would require an experimental characterization of the ME coefficients of the in-house manufactured substrates and we are in the process of doing so. Instead, for the time being, a single layer commercially available 2mm thick ferrite substrate was used with an external bias (H₀) control to demonstrate the beam-steering capability of the proposed miniature LWA. Excellent beam steering was achieved over 80° by changing H₀ by ±500Oe. As the ferrite’s material properties are a function of H₀ (related to H₀ saturation magnetization 4πM₀ and demagnetization fields inside the ferrite [4], [5]) changing H₀ is equivalent to the proposed tuning method. Still, the required VDC for a change of ±500Oe in the magnetic field strength needs to be experimentally determined. Design and fabrication of the magneto-electrics based LWA is in progress and details will be presented at the conference.

FIGURE 1. Layout of the proposed magnetoelectric substrate comprised of ferrite layer, piezoelectric phase and magnets for tunability.

II. MINIATURIZED NON-RECIPROCAL LWA DESIGN

Composite-right-handed (CRLH) transmission lines (TLs), incorporating series capacitors and shunt inductors, support dominant fast waves at low frequencies and therefore lead to significantly miniaturized LWAs. In this work, coupled CRLH TL pair was used to further miniaturize the LWA and to realize nonreciprocal radiation by utilizing mode coupling [6]. The unit-cell of the proposed design is depicted in Fig. 2(a), where a 0.6mm thick PCB (with dielectric Rogers RT/Duroid 3010, εᵣ=10.2, tanδ=0.0023) with overlapping transmission line sections was used as a superstrate and placed on a 2mm thick low-loss AL-800 substrate with 4μMs=80Oe, ΔH=300Oe, εᵣ=14.2, tanδ=0.001. An external DC magnetic field of strength H₀ was applied normal to the ground plane to control ferrite’s material properties. The advantage of the given design is that much larger capacitances were attained by overlapping the TL arms. For this specific design, the series capacitance (2Cₑᵣ) in each unit-cell was ~2.6pF, a value that is challenging to realize using interdigital capacitors.
To calculate the effect of increased capacitance and mode coupling on circuit miniaturization, the $K$-$\omega$ dispersion diagram of single and coupled CRLH TLs was computed using the T-matrix approach and compared to the dispersion of regular TLs [6]. It was found that the CRLH TLs reduced the excitation of fast waves from a frequency of 5.74GHz (for a regular TL) down to 1.73GHz (and 1.63GHz for the coupled TLs). This implies a miniaturization by a factor of 3.5.

Next, the propagation wavenumber of leaky-waves ($\gamma=\beta+\alpha$) was calculated as a function of the bias field. A goal was to predict the scanning properties of the given design. Figure 2(b) depicts the computed phase constant $\beta$ for different bias field strengths. It is clearly observed that $\beta$ changes as a function of $H_0$, implying scanning of the radiated beam ($\theta_0=\sin^{-1}(\beta/k_0)$). A key point in realizing wide angle beam-steering via small changes in $H_0$ is to operate the LWA relatively close to the ferromagnetic resonance (FMR) of the ferrite. As such, $\mu$, of the ferrite become more sensitive to changes in $H_0$. Otherwise, $\mu$, becomes $\sim$1 and the LWA becomes insensitive to $H_0$. For this particular design, $H_0$ was chosen to be $\sim$1800 Oe, corresponding to $H_i$($=H_0/4\pi\mu_i$) of approximately 1000 Oe [5]. As a result, the FMR occurred at 2.8GHz, whereas the operating frequency was 1.85GHz. Another important property of the proposed LWA is its nonreciprocity. Ferrites biased transverse to the propagation direction exhibit nonreciprocal field displacements effects and cause the propagation characteristics of forward and backward propagating waves to become different [6]. This is essential to realize different transmitting (TX) and receiving (RX) ports (indicated by port 1 and port 2 in Figure 2(c), respectively).

III. EXPERIMENTAL VALIDATION

For the experimental validation, a finite LWA prototype was fabricated and tested in the presence of $H_0$ supplied by a permanent magnet block of 15.25cmx7.6cmx3.1cm (see Fig. 2(c)). The final LWA had a footprint of 1cmx12.7cm and was only $\sim$1/70 thick, making it highly portable. In Figure 2(d), a maximum of 12.1 dB contrast is observed between TX and RX antenna gains at port 1. The TX and RX antenna pattern was also scanned in the $E$-plane ($\gamma$-$\phi$ plane) by controlling the bias field, $H_0$. This was done by changing the distance between the magnet block, corresponding to a change in $H_0$ by $\pm$50 Oe. Corresponding RX antenna pattern measured at port 1 is depicted in Figure 2(e) for 1.85GHz. It is clearly observed that beam can be scanned in the $E$-plane from $\theta_0$=45° to 35° degrees by decreasing the external bias field by 100 Oe. The antenna gain varies between 3.5dB and 5dB as the beam is scanned. RX pattern measured at port 2 is almost identical to TX pattern measured at port 1. As shown, this innovative concept offers beam-steering at a single frequency and over a wide range of steering angles. Another observation is that half power beamwidth of the TX antenna pattern is $\Delta\theta=65^\circ$. This relatively large beamwidth is attributed to the variations in $H_0$ along the length of the antenna that caused each unit-cell to radiate at a slightly shifted direction. Additionally, the antenna was only $\lambda/4$long. The beam can be made narrower by increasing the length of the antenna. However, making the antenna longer than 15.25cm would cause the ferrite substrate to be partially biased and hence lossy. Therefore, antenna performance can be improved only by redesigning it to operate at higher frequencies, which will be presented in the

Figure 2. (a) Unit-cell of the coupled CRLH LWA and (b) propagation wavenumber $\gamma=\beta+\alpha$ for 3 different values of external bias field. (c) Nonreciprocal LWA layout with 24 mil thick printed circuit board placed on top of the 80 mil thick AL-800 ferrite substrate. (d) Measured TX and RX gains at port 1 vs. frequency. (e) Scanned TX pattern in the $E$-plane at 1.85GHz by changing the external bias field.

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