Beam Scanning Antennas Based on Pseudo Traveling Wave Resonators

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Abstract—A pseudo-traveling wave resonator and its application to beam scanning antennas are reviewed. The resonator is a new type of transmission-line resonator, and is composed of a phase-nonreciprocal composite right/left handed (CRLH) transmission line and reflectors at both ends. The resonant frequency is independent of the resonator’s size. In addition, the resonator has traveling wave type field profile with uniform magnitude and finite gradient of phase distribution along the line. The phase gradient is determined by the phase nonreciprocity of the employed CRLH transmission line. We can control the phase gradient by changing an external dc magnetic field applied to ferrite materials included in the line. Leaky wave radiation from such resonators with open-boundaries forms an obliquely directional beam. Control of the phase distribution leads to the beam scanning. The proposed antenna has an advantage of low beam squint and high radiation efficiency, compared to conventional leaky wave antennas.

I. INTRODUCTION

Metamaterial-based microwave components/devices, in general, utilize their attractive phase characteristics of guided waves, such as forward/backward wave propagation. Recently, from a phase controlling point of view, nonreciprocal composite right/left handed (CRLH) transmission lines were proposed, which support a dominant right-handed (RH) mode with positive refractive index in one direction of the transmitted power, and a dominant left-handed (LH) mode with negative refractive index in the opposite direction [1]-[4]. The transmission lines were implemented into nonreciprocal leaky-wave antennas with obliquely unidirectional beam radiation [1],[2] and with the gain enhancement due to constructive interference between leaky waves from an incident wave and the reflected waves at the terminal [5] and also in pseudo-traveling wave resonators with reflectors at both terminals open or shorted permitting multiple reflections [6]. The pseudo-traveling-wave resonator is a new-type of transmission-line resonator and has the field profiles with the uniform magnitude and gradient of the phase distribution along the resonator. We named it with “pseudo” because it is not a conventional pure traveling wave resonator in that the transmitted power flow on the resonator for an ideal case without any losses is cancelled out, due to the interference of forward and backward wave propagations. The phase gradient of field distribution depends on the applied dc magnetic field and magnetization in the ferrite. Recently, pseudo-traveling wave resonator was investigated numerically and experimentally under the unsaturated magnetization regime, and the new-type beam steering antenna based on the resonator was demonstrated [7], [8]. It is a short-ended transmission-line resonator and is composed of a nonreciprocal phase-shift CRLH microstrip line using polycrystalline yttrium iron garnet rod. The resonator operates as a zeroth-order resonator if there is no external dc magnetic field, and the radiation beam from the resonator directs to broadside. By increasing an externally applied dc magnetic field normal to the substrate, the effective dc component of magnetization in the ferrite increases under the unsaturated region. Then, phase gradient of the field distribution along the resonator is also enhanced. As a result, the radiation beam direction changes obliquely with respect to broadside. Continuous backfired-to-endfire beam steering was demonstrated with almost constant gain. In addition, numerical simulation results show considerably high radiation efficiency of more than 90 %, and the beam squint were found relatively low, compared to conventional leaky wave antennas.

II. CONFIGURATION OF PSEUDO-TRAVELING WAVE RESONATOR

In this section, a pseudo-traveling wave resonator is reviewed. In Fig. 1, the equivalent circuit model and the phase matching condition are illustrated. In Fig. 1(a), the quantities β+ and β− denote phase constants of these dominant CRLH modes, whose signs are taken so that the direction of the transmitted power is positive. Fig. 1(b) shows the automatic phase matching condition describing the phase distribution for traveling waves experiencing round trip on the resonator. The phase of an incident forward wave mode propagating to the right is delayed whereas the phase of the backward wave mode that is reflected at the terminal and going back to the left gets advanced. When both gradients of the phase distribution are exactly the same, the total phase shift always vanishes to achieve the resonant condition. The resonator can be implemented into beam scanning antennas by using the gradient of phase distribution on the resonator, when the...
waveguide has open boundaries and dominant modes on the line is leaky wave.

III. REDUCED BEAM SQUINT AND HIGH EFFICIENCY

An advantage of the pseudo-traveling wave resonator antenna is robust stability of steering beam direction against perturbation of the operational frequency. For conventional CRLH-transmission-line-based leaky wave antennas, beam direction is vulnerable to perturbation of the operational frequency. The variation of beam direction \( \theta \) with respect to \( \omega \) is given by [9]

\[
\frac{d\theta}{d\omega} \approx \frac{1}{\sqrt{\beta_0^2 - \beta_c^2}} \left( \frac{d\beta}{d\omega} \right)_{\omega=\omega_c} = \frac{1}{\sqrt{\beta_0^2 - \beta_c^2}} \left( \frac{1}{v_g} - \frac{1}{v_p} \right)
\]  

(1)

where \( v_g = d\omega/d\beta \) is group velocity, and \( v_p = \omega_c/\beta_c \) is phase velocity. We have taken the center frequency \( \omega_c \) and the phase constant \( \beta_c \). A factor \( 1/\sqrt{\beta_0^2 - \beta_c^2} \) in (1) slowly varies with the operational frequency and is relatively constant except for frequencies in the vicinity of singular points \( \beta_c = \beta_0 \). Therefore, \( d\theta/d\omega \) is almost proportional to another factor of a difference between reciprocal of the group velocity \( v_g \) and that of phase velocity \( v_p \). In the fast wave region where leaky waves are radiated, the phase velocity \( v_p \) exceeds a speed of light in vacuum \( c \) whereas the group velocity \( v_g \) is less than \( c \). Therefore, \( d\theta/d\omega \) essentially remains finite. Especially for cases at frequencies in the vicinity of the intersection of dispersion curves, the fluctuation \( d\theta/d\omega \) becomes significant and is approximately proportional to \( 1/v_g \) because \( 1/v_p \) is nearly zero with \( \beta \equiv 0 \).

On the other hand, the proposed antenna is basically resonant-type and the beam direction is much more robust against the perturbation of the frequency, compared to conventional leaky wave antennas. The perturbation of the beam angle is given by

\[
\frac{d\theta}{d\omega} = \frac{1}{\sqrt{\beta_0^2 - \beta_{NR}^2}} \left( \frac{d\beta_{NR}}{d\omega} \right)_{\omega=\omega_c} - \frac{\beta_{NR}}{\omega_c}
\]  

(2)

where \( \beta_{NR} \) in (2) denotes the phase nonreciprocity at the center frequency, \( \beta_{NR}(\omega_c) \), as illustrated in Fig. 2. From (2), the perturbation of beam angle for the proposed antenna is approximately proportional to a factor of the difference between the first derivative of the phase nonreciprocity with respect to the frequency and the ratio of phase nonreciprocity to the frequency. In the present case, the derivatives of the phase nonreciprocity for simulated and measured results are much smaller than the group delay of the same CRLH modes in (1). The second term \( \beta_{NR}/\omega \) in parentheses of (2) is less than the first term. Thus, the robustness of the beam directions against modulated signals for the proposed resonator antenna is verified by the mechanism of the leaky wave radiation and the nonreciprocal dispersion diagram. It is noted that for the proposed pseudo-traveling wave resonator antennas, the beam squint can be drastically reduced without any additional efforts.

In addition, the proposed antenna has considerably high radiation efficiency. Fundamental mechanism of leaky wave radiation from the resonator antenna is the same as conventional leaky wave antennas, but the efficiency is significantly improved by using multiple reflections at both ends. The efficiencies for both cases with and without dc magnetic fields are approximately the same with each other. When the matching condition is well-achieved, the typical efficiency was more than 90 %.

IV. CONCLUSION

The pseudo-traveling wave resonator and its application to beam scanning antennas were reviewed. We can control the phase gradient of the field distribution by changing an external dc magnetic field applied to ferrite materials included in the line. Leaky wave radiation from such resonators with open-boundaries forms an obliquely directional beam. The
control of the phase distribution leads to the beam scanning. This antenna has an advantage of low beam squint and high radiation efficiency, compared to conventional leaky wave antennas.

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REFERENCES