PEMC Metamaterial Surface whose Gyrotropy is provided by Traveling-Wave Ring Resonators

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Abstract

A PEMC metamaterial surface consists of traveling-wave ring resonators is proposed. The fundamental requirement to establish PEMC is non-reciprocal gyrotropy. The gyrotropy is realized by a ferrite-free traveling-wave ring resonator metamaterial structure. The prototype device clearly indicates the expected non-reciprocal gyrotropy, which is equivalent to the proof of PEMC realization.

Keywords: Perfect electric magnetic conductors (PEMC), gyrotropy, Faraday rotation, traveling-wave resonator, metamaterial.

1. Introduction

Artificial boundary conditions, such as the perfect magnetic conductor (PMC) condition, are promising techniques to enhance the performance and reduce the size of planar antennas. Recently, a novel boundary condition, the perfect electric magnetic conductor (PEMC) condition, was introduced as the generalization of PMC/PEC [1] and was realized by a grounded ferrite substrate using Faraday rotation in [2]. However, the implementation in [2] requires a low loss and uniformly biased magnetic material using a bulky permanent magnet, which leads to a large and heavy structure. This paper introduces a novel traveling-wave ring metamaterial structure which achieves the same result as the grounded ferrite without its disadvantages.

2. PEMC Surface from Faraday Rotation in a Grounded Ferrite Slab

Figure 1 explains the principle of the PEMC surface realized in [2], which is based on Faraday rotation and reflection in a grounded and ferrite substrate. Figure 1(a) shows the structure. As shown in Fig. 1(b), the incident electric field $\mathbf{E}_i$ rotates by θ due to Faraday rotation as it propagates from the surface of the ferrite slab to the ground plane, where it becomes $\mathbf{E}_{g-}$. On the ground plane, $\mathbf{E}_{g-}$ flips to $\mathbf{E}_{g+}$ to satisfy the tangential electric field boundary condition. The field is then reflected to the +z direction, and gains an additional angle θ when it reaches the surface, to become $\mathbf{E}_r$. The total field at the surface is $\mathbf{E}_i + \mathbf{E}_r$, and is at an angle $\pi / 2 - \theta$ with respect to $\mathbf{E}_i$. Similarly, the incident field $\mathbf{H}_i$ rotates by 2θ , however without being flipped on the ground plane, and the total field $\mathbf{H}_i + \mathbf{H}_r$ is at the *same* angle $\pi / 2 - \theta$ with respect to $\mathbf{E}_i$. Therefore, the total electric and magnetic fields are collinear at the interface, which is the corresponds to a general PEMC for tangential electromagnetic fields [1], with the possible particular PEC cases for $\theta = n\pi$ and PMC for $\theta = (n + 1/2)\pi$. It should be noted that the non-reciprocity of the polarization rotation is indispensable to obtain a PEMC surface. A reciprocal gyrotropic system would have the reflection angle cancelling out exactly the incidence angle, which would prevent such an effect, and lead to simply reflection without change in polarization. In this work, this non-reciprocity is realized by artificial magnetic gyrotropy, which is provided by traveling-wave ring resonators.

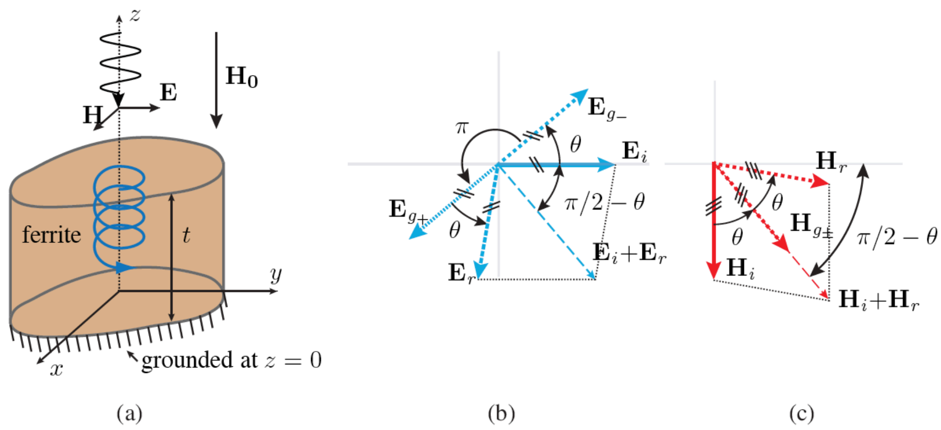

Fig. 1 Realization of a perfect electromagnetic conductor (PEMC) interface using Faraday rotation in a grounded ferrite slab. (a) Structure. (b) Electric field evolution. (c) Magnetic field evolution.

3. Principle of Artificial Gyrotropy from Traveling-Wave Ring Resonance

Figure 2 shows the principle of artificial gyrotropy from a traveling-wave ring resonator. As shown in Fig. 2(a), the ring supports a traveling-wave (as opposed to a standing wave) thanks to the presence of an isolator with a gap. This isolator is typically realized with a FET transistor biased in its common source configuration and exhibiting a phase shift of 180°. Taking into account the 180° phase shift of the isolator, the resonance corresponds to circumferential length of $l = \lambda/2$. Fig. 2(b) shows the field distributions along the ring at instants separated by a quarter of the harmonic period for the resonance of Fig. 2(a). It shows that a rotating magnetic dipole moment $\mathbf{m}$ is generated in the ring as a result of the azimuthal unidirectionality of the wave propagation along it.

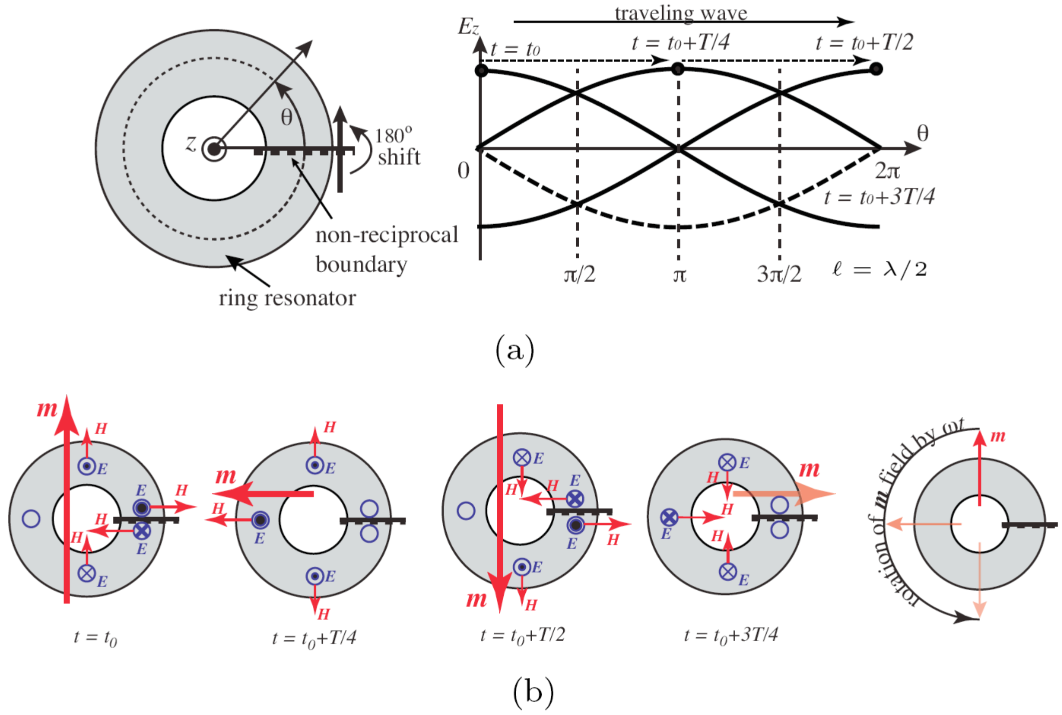

Fig. 2 Proposed generation of gyrotropy by a traveling-wave a ring resonator obtained by inserting an isolator (e.g. implemented by transistor) within a small gap of the ring. (a) Ring resonator using a localized isolator with 180° phase shift, supporting a traveling wave for the first resonant mode where the circumference is $l = \lambda/2$. (b) Explanation of gyrotropy from a rotating magnetic dipole moment $\mathbf{m}$.

4. Experimental Verification of PEMC by Artificial Gyrotropy

Figure 3 shows the complete proposed PEMC metamaterial surface. As shown in Fig. 3(a), the unit cell is a super-cell which consists of four rings in terms of their isolator so as to provide overall a 90° azimuthal symmetry; the RF part (ring resonators and FET isolators) are placed at the front side (side to be illuminated by the electromagnetic wave) and the DC part (bias network) is placed at the back side. The two parts are isolated from each other by a ground plane. Fig. 3(b) shows the front side of the prototype, which consists of 3x3 super-cells (36 rings). Fig. 3(c) shows the backside of the prototype, and the bias network for the FETs.

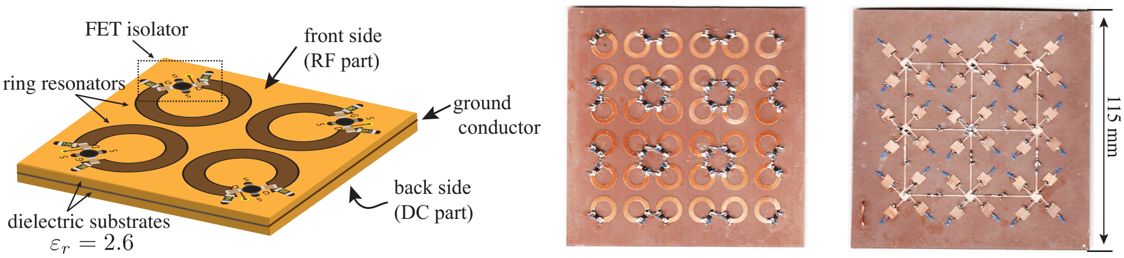

Fig. 3 Proposed PEMC metamaterial surface consisting of non-reciprocal traveling-wave ring resonators. (a) Unit-cell, consisting of 4 gyro-ring resonators. (b) Prototype front side. (c) Prototype backside.

Wave reflection from the surface of Fig. 3(b) is measured by the monostatic setup shown in Fig. 4, where the angle θ between the two horns can be varied shown in Fig. 4(a), in order to measure gyrotropy. Fig. 4(b) shows the whole setup, where the separation between ports and DUT is 1.5 m. The two horns are connected to a VNA.

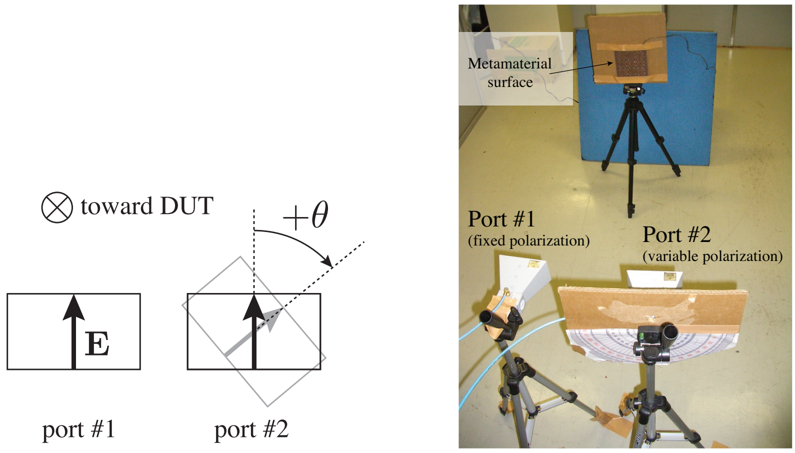

Fig. 4 Measurement setup. (a) Two horn antennas with variable relative orientation angle. (b) Whole setup showing the two horn antennas and the PEMC surface under test.

Figure 5 shows the measured transmission characteristics between the two horns for different relative angles θ and bias voltages V_{DS} of the FETs. Fig. 5(a) shows the change of transmission characteristics for V_{DS} = 0 and 0.57 V at $\theta = 0^\circ$, where a small change is observed after activation of the FETs. The bias voltage of 0.57 V was chosen at the limit of instability for maximum gyrotropy without oscillation. No significant non-reciprocity can be observed in this setup. By setting an angle of $\theta = -75^\circ$ between the two horns, a strong non-reciprocity of around 10 dB appears, as shown in Fig. 5(b), at two frequencies (7.25 and 7.6 GHz). When the angle is changed to $\theta = +75^\circ$ in Fig. 5(c), the two isolation peaks are reversed. This behaviour is *exactly* that of a grounded ferrite slab under Faraday rotation (Fig. 1, [3]). This demonstrates the gyrotropic response of the proposed ring metamaterial surface, and thus its capability to provide a PEMC boundary.

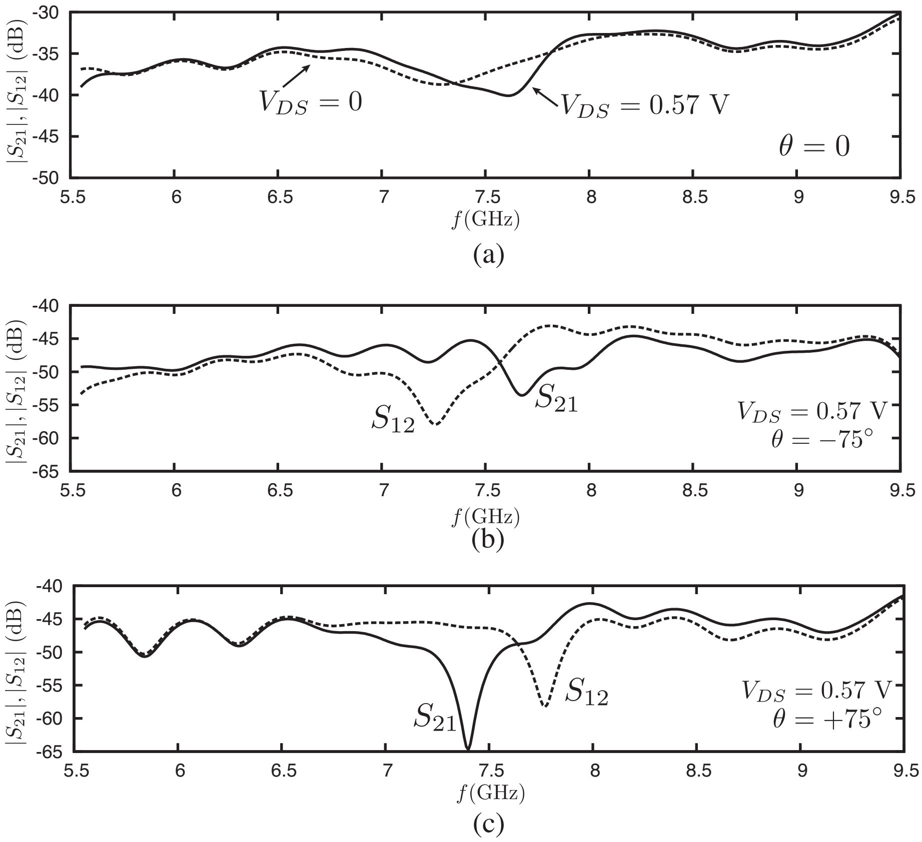

Fig. 5 Measured transmission characteristics between two horns for different orientation angles θ and FET bias voltage. (a) $\theta = 0$, V_{DS}=0, 0.57 V. (b) $\theta = -75^{\circ}$, V_{DS}=0.57 V. (c) $\theta = +75^{\circ}$, V_{DS}=0.57 V.

5. Conclusion

A PEMC metamaterial surface based on traveling-wave ring resonators has been proposed and experimentally demonstrated. This is a proof that the metamaterial surface can achieve a PEMC boundary.

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