Spatial Nonreciprocal and Nongyrotropic Structure

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***Abstract*— A spatial non-reciprocal and a non-gyrotropic structure is proposed based on coupled resonators used in conjunction with a magnetless isolator, and demonstrated using full-wave simulations.**

I. Introduction

Spatial systems are ubiquitous across all fields of science and engineering ranging from microwaves to optics, to manipulate electromagnetic wavefronts in space. A vast amount of literature in optics related to ultrafast optical signal processing exist and is extensively used for optical field manipulations using spatial systems such as lenses, optical filters, polarizers and spatial light modulators [1]. Similar developments in the radio frequency ranges exist typically based on frequency selective surfaces (FSSs) [2] and antenna beamformers using transmit reflect arrays [3]. Recently, there has been a renewed interest in two-dimensional metasurface structures which are functional extensions of FSSs and reflect arrays, for realizing generalized wavefront transformations [4].

One class of such spatial systems involve non-reciporcity for applications involving wave shielding such as in non-reciprocal radomes [5]. Non-reciprocal radomes protect signal transmitter from external interference while enabling perfect transmission through them [5], [6], [7]. These non-reciprocal spatial systems are essentially based on Faraday rotation achieved using magnetic materials like ferrites. While they provide the sought non-reciprocity, they suffer from a fundamental limitation: they are gyrotropic in nature and thereby they *rotate* the polarization of the input wave as it passes through the surface. This features is not always desired, and there is a need to device a *non-reciprocal* and a *non-gyrotropic* spatial system so that the waves polarizations are preserved through the structure. Moreover, the ferrite based structures are bulky and require permanent magnets, thereby limiting the usefulness of conventional spatial non-reciprocal systems.

This paper presents a novel non-reciprocal, a non-gyrotropic and a non-magnetic spatial structure to solve the issues mentioned above exploiting the magnetless nonreciprocity in metamaterials [8], [9], [10], [11], [12], [13].

II. Proposed Spatial Structure

A. Principle

Figure 1(a) shows the functional behaviour of an ideal spatial non-reciprocal and nongyrotropic structure. When excited with a input wave $\psi_{\text{in},1}$ at a frequency ω_0 from the left half of the structure with a polarization x, the wave simply passes through the structure with perfect transmission, i.e. $\psi_{\text{out},2} = \psi_{\text{in},1}$, *and* preserving its polarization at the same time. On the other hand, when excited from the right half of the structure with the same $x-$polarized input wave $\psi_{\text{in},2}$, it does not pass through so that $\psi_{\text{out},1} = 0$. The condition $\psi_{21} \neq \psi_{12}$ ensure non reciprocity and no rotation of wave polarization ensures nongyrotropy.

Such a structure can be physically implemented using the proposed concept of Fig. 1(b). The ideal structure of Fig. 1(a) can be seen as a series cascade of three independent elements: an input pickup antenna, a non-reciprocal device and an output radiating antenna. The input antenna accepts the wave input and feeds it to a non-reciprocal element, e.g. isolator. The output of the isolator is then used to feed the output antenna to re-radiate the fields constituting the output of the system. The input and output antennas are co-polarized with respect to each other, ensuring no rotation of fields polarizations between the input and output, thereby guaranteeing a non-gyrotropic response. This arrangement thus emulates an ideal nonreciprocal and nongyrotropic structure of Fig. 1(a).

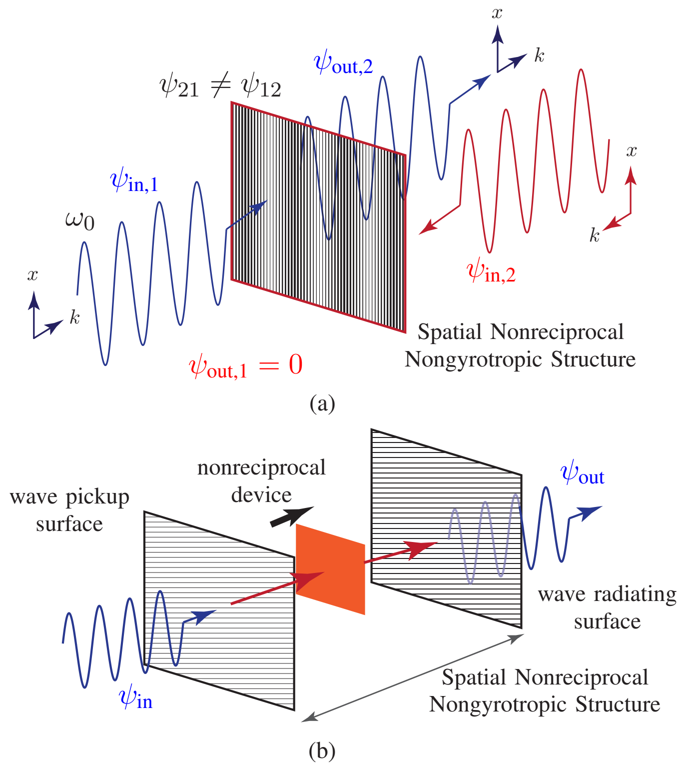

Fig. 1. Nonreciprocal and nongyrotropic structure. a) Functional illustration. b) Proposed principle.

B. Implementation

Typically the input pickup and output radiating antennas are resonant in nature. In such a case, the proposed structure of Fig. 1(b), can be seen as two resonators coupled via non-reciprocal element in between. Two estimate the modes of the system, let us first consider the circuit equivalent of a reciprocal case, as shown in 2(a).

This coupled system supports two modes: synchronous mode (even mode) and asynchronous mode (odd mode) [14][15]. The Even mode exists for the in-phase excitation of the two resonators (open-circuit), leading to a resonance frequency ω_e identical to that of the isolated resonators.

$$\omega_e = \frac{1}{\sqrt{LC}}. \tag{1}$$

The odd mode on the other hand corresponds to the out-of-phase excitation of the two resonators and the mutual inductance [1] consequently interacts with the two resonators and shift the resulting resonant frequency to

$$\omega_o = \frac{1}{\sqrt{(\frac{LL_m}{L_m+2L})C}}. \tag{2}$$

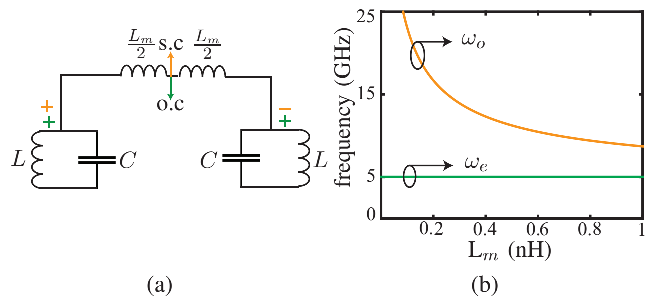

Fig. 2. Coupled resonators and their modes. a) Schematic. b) Even- and odd-mode resonant frequency as function of the mutual inductance L_m.

The relation between the even and odd-mode resonant frequency and the coupling inductance is plotted in Fig. 2(b). While the even mode is independent of L_m, the odd-mode frequency ω_o monotonously approaches ω_e.

Now if such a coupled system is driven with an input excitation and incorporated with a non-reciprocal element such as an isolator, as illustrated in Fig. 3(a), the corresponding S-parameter response is shown in Fig. 3(b). Strikingly, only the even-mode of the coupled resonator survives, and this mode exhibits non-reciprocal transmission characteristics between the input and the output ports. This fact forms the basis of devising a spatial non-reciprocal and a non-gyrotropic structure of Fig. 1(a).

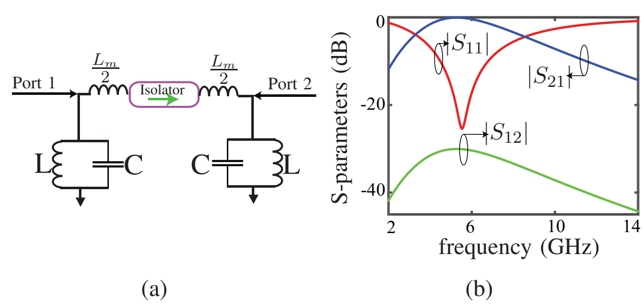

Fig. 3. Coupled LC resonators connected through an ideal isolator. a) Schematic, and b) typical circuit response.

[1]A inductive coupling is taken here as an example to illustrate the concept. In general, the coupling could be both capacitive or inductive.

The coupled resonator circuit of Fig. 2, can next be adapted towards a spatial structure, by replacing the LC resonators with two co-polarized resonating patch antennas coupled through a connecting via as shown in Fig. 4(a). The presence of the ground plane isolates the two patch resonators, restricting the wave coupling only through the connecting via between them. Next inserting a magnetless isolator [8] between the two patch resonators providing the non-reciprocity, FET transistor (a unilateral device) biased with no gain in the forward direction could be seen as a magnetless isolator. A single unit-cell of the spatial non-reciprocal structure is formed, which can be periodically repeated to form the overall structure. The co-polarized patches, to recall, preserves the input field polarization, thereby ensuring a non-gyrotropic response.

C. Results

Figure 4(b) shows a typical full wave simulated response of such a non-reciprocal and non-gyrotropic structure corresponding to the structure of Fig. 4(a) with an ideal isolator inserted between the two patch resonators. A strong non-reciprocal response is achieved and due to the co-polarized patch antennas and the magnetless isolator employed, no rotation of the field components is observed. This confirms the operating principle of the proposed spatial structure.

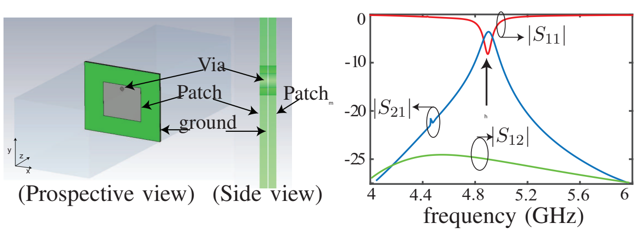

Fig. 4. Full-wave implementation of a spatial nonreciprocal and nongyrotropic structure. a) Proposed structure, b) Typical S-parameters computed in CST Microwave studio corresponding to the structure of Fig. 4(a) used with an ideal isolator sandwiched in between the two patch antennas.

III. Conclusion

A spatial nonreciprocal and a nongyrotropic structure has been proposed based on coupled resonators used in conjunction with a magnetless isolator, and has been demonstrated using full-wave simulations. The two coupled resonators were realized as co-polarized patch antennas coupled through an isolator, thereby exhibiting a strong non-reciprocity at the isolated resonant frequency of the patch antennas used. The structure demonstration and detailed description is currently under process and will be reported elsewhere.

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