Terahertz magnetic plasmon waveguides

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***Abstract*—A design of subwavelength terahertz waveguides is presented in this manuscript. The structure is composed of a linear chain of split-ring resonators (SRRs), i.e., artificial magnetic atoms. The energy transport along the chain can be described by magnetic plasmon propagation sustained via magnetic dipoles and conductive coupling. The simulation result shows a slow-light effect with minimal loss over a broad spectrum.**

I. Introduction

Terahertz communication has become increasingly significant in the last few years [1], [2]. Existing low-frequency communication bands are almost fully utilized by diverse applications requiring a vast amount of bandwidth. A move towards data transmission at the terahertz range will lead to an increase in data bandwidth over 10 Gbps in short-distance applications [3]. Terahertz communication is therefore currently a focus of extensive research efforts. Despite that, terahertz waveguides compatible with optical integrated circuits have yet to become available.

It has been suggested that linear chains of metamaterial resonators, or magnetic atoms, can serve as subwavelength planar waveguides at microwave, infrared, and optical bands [4], [5]. The electromagnetic energy can be transported along these periodic channels by exploiting near-field interactions among induced magnetic dipoles. This type of wave propagation is due to magnetic plasmon (MP) waves. Inherent to metamaterial resonators, the transverse size of these MP waveguides is much smaller than the wavelength of the excitation wave.

This article presents an implementation of a subwavelength planar terahertz waveguide supported by MP resonances. The design is based on concatenated split-ring resonators. The use of square SRRs simplifies the fabrication. The simulation shows a promising result. The planar design and subwavelength size of the waveguide make it a potential candidate for on-chip applications.

II. Design

A square and planar SRR in Fig. 1(a) is chosen as a building block for the waveguide. The dimensions are designed so that the ring resonates in the terahertz spectrum. A terahertz waveguide is formed by physically connecting a number of these SRRs into a linear chain, as shown in Fig. 1(b). The cascaded rings overlap to maximize the coupling strength through the conduction current. The structure is made of a copper-cladded PTFE substrate with a copper thickness of 17 μm and PTFE thickness of 50 μm. The relative permittivity and loss tangent of PTFE are 2.28 and 0.02, respectively, whereas the complex conductivity of copper can be described by surface impedance with the Drude model [6]. The designs are simulated by using the transient solver of CST Microwave Studio.

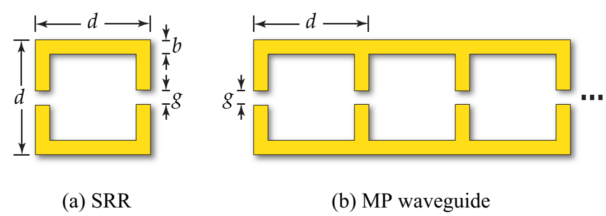

Fig. 1. Design of SRR and waveguide. (a) Single SRR or magnetic atom. (b) MP waveguide from cascaded SRRs. The dimensions are as follows: $d = 200$ μm, $b = 30$ μm, $g = 30$ μm. The waveguide period is equal to 170 μm.

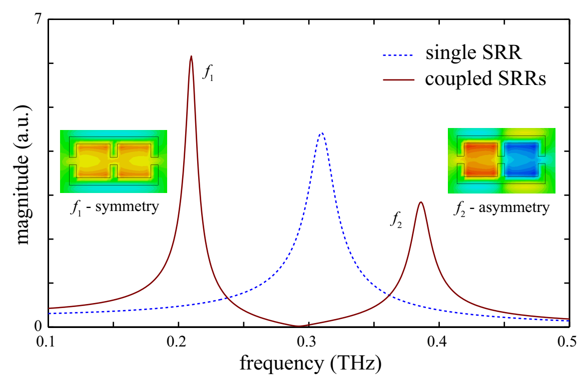

Fig. 2. Characteristics of coupled resonators. The profiles show the transversal magnetic-field amplitude at the center of a ring. The insets depict the instantaneous field distributions of the magnetic field normal to the rings at two resonance frequencies.

III. Results

Initially a system of only two coupled resonators is modelled to investigate the MP coupling behaviors. Figure 2 shows the transversal magnetic-field amplitude for the single and coupled resonators. The strong coupling between the two resonators causes resonance splitting into two hybridized modes at $f_1 = 0.21$ and $f_2 = 0.39$ THz. From the insets of Fig. 2, it is clear that the lower and upper resonances

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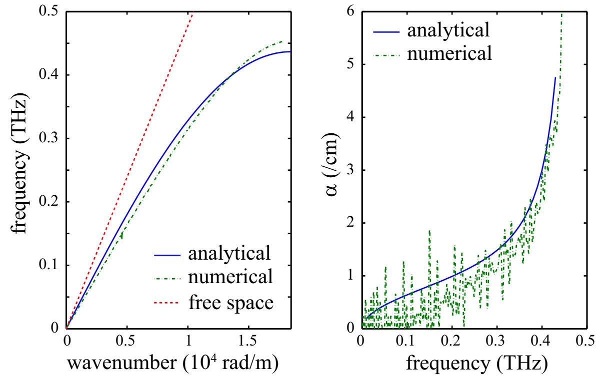

Fig. 3. Waveguide characteristics from analysis and simulation. (a) Dispersion, and (b) absorption.

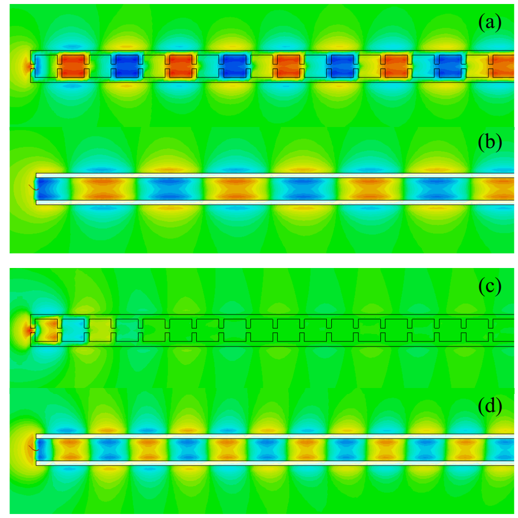

Fig. 4. Tranversal magnetic field distribution. The magnetic field distributions over the MP waveguide (a,c) compared with that over the coplanar strips (b,d). The comparison is made at 0.3 and 0.5 THz. Note the different scales are used for the MP waveguide and transmission line.

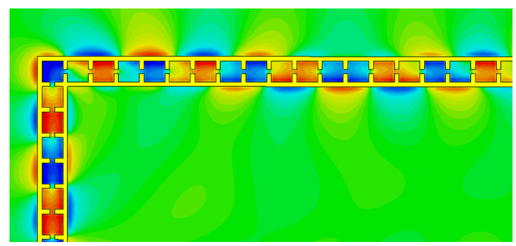

Fig. 5. Field distribution around the corner of the waveguide. The transversal magnetic field distribution is plotted at 0.3 THz. The wave propagates from the bottom upwards and to the right.

are associated with the symmetric and asymmetric modes, respectively. According to the quasistatic dipole-dipole interaction model, it can be deduced that the electric dipole coupling dominates the hybridization. An additional analysis with a Lagrangian formalism reveals that the electric coupling coefficient between the two resonators approaches unity, whilst the magnetic coupling coefficient is close to zero.

Figure 3 shows the characteristics of the proposed terahertz MP waveguide obtained analytically and numerically. The analytical results are from Lagrangian formalism of the structure assuming an infinite chain of magnetic resonators. Both the analytical and simulation results are in general agreement. The dispersion curve bears a similarity to that of surface plasmon polaritons. At low frequencies the wavevector of the MP waveguide is close to the line representing free-space propagation, and therefore the effect of wave confinement is weak. As the frequency increases, the wavevector becomes larger, suggesting a slow-light effect and energy confinement in the waveguide. The frequency of 0.45 THz defines the 'magnetic plasmon' frequency of the waveguide, where the wavevector approaches infinity and the group velocity is zero. The absorption curve in Fig. 3 suggests relatively low transmission loss from DC to near the magnetic plasmon frequency.

The magnetic field distribution over the waveguide is illustrated in Fig. 4 in comparison to that over the conventional coplanar strips. At 0.3 THz the wave shortening and lateral field confiement is obvious in the MP waveguide. At 0.5 THz, above the cutoff frequency, no wave propagation is observed in the MP waveguide, demonstrating its filter behavior. An additional numerical result in Fig. 5 shows the field distribution around a corner of the waveguide. Interestingly the energy can be carried around the 90° corner with low radiation loss. This capability will be useful for integration of the waveguide on chip, where the space is considerably limited.

IV. Conclusion

An implementation of a coupled resonator terahertz waveguide is presented. The waveguide can sustain MP waves through a series of coupled and connected SRRs. The simulation results demonstrate promising waveguide characteristics. As the dispersion, group velocity, field enhancement, and energy flow of terahertz waves can be freely tuned in the specifically designed periodic systems, the implementation of this waveguide will open a wide range of potential applications, particularly in terahertz integrated circuits.

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