Metamaterial Absorber with Active Frequency Tuning in X-band

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***Abstract*-This paper presents the design, fabrication, and measurement of an active frequency tunable metamaterial absorber. The unit cell of the metamaterial absorber consists of a metallic strip on the top layer of the fully grounded dielectric substrate, with a varactor loaded at the slit in the middle of the central strip. Simulation and measurement results show that by tuning the bias voltage applied on the varactors, the peak absorption frequency can be tuned about 0.44 GHz with the peak absorption greater than 95%. Field analysis reveals that the unit cell of the absorber works as the microstrip resonator which exhibits matched input resistance to the incident waves.**

I. INTRODUCTION

Electromagnetic (EM) wave absorber is a functional material that absorbs incident EM energy. Conventional EM absorbers are mainly realized by using material with high ohmic loss and magnetic polarization loss [1-3].

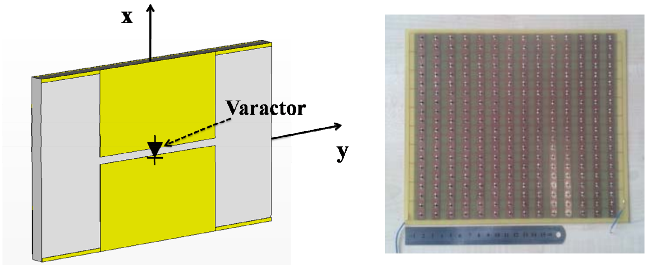
The metamaterial absorber (MA) is another new type of EM absorber proposed recently [4]. It is normally composed of electrical small unit cells arranged periodically in a 2D plane. Each unit cell can be regarded as the resonant circuit. At resonance, MA exhibits purely effective surface resistance matched to incident EM wave impedance to achieve efficient wave absorption. The MA enjoys the features of light weight and low profile, but suffers narrow absorbing frequency bandwidth [5-6].

Since MA is realized through artificial design of the unit cell structure, one unique advantage of MA is that more functions than absorbing waves can be combined into MA, such as absorbing frequency tuning, polarization dependent absorbing, etc [7-8].

In this paper, an active frequency tunable MA in X-band is presented employing the microstrip resonator mode. It is realized by integrating varactor into the unit cells of the MA. Simulation and measurement show that by tuning the bias voltage applied on the varactors, the peak absorption frequency can be tuned about 0.44GHz with the peak absorption greater than 95%. Field distribution is analyzed to explore the working mode and physical origin of the property.

II. STRUCTURE AND WORKING MECHANISM

The unit cell of the proposed tunable MA is shown in Fig. 1(a). It consists of a metallic strip on the top layer of the fully grounded dielectric substrate. In order to dynamically control the absorbing frequency, a varactor is loaded at the slit in the middle of the central strip. The bias circuit is designed and positioned at the upper and lower edge of the unit cell to supply bias voltages onto the varactors.

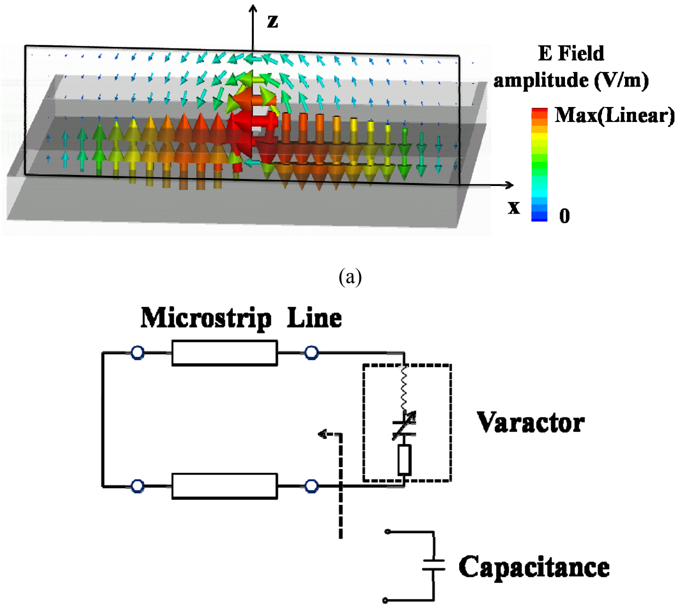


(a) (b)

Fig. 1. (a) A schematic of the unit cell of the actively tunable MA. (b) The fabricated sample board.

Since the whole MA is a periodic structure, we only need to analyze one unit cell using the periodic boundary condition according to Floquet theorem. Because the unit cell structure is symmetric with respect to both x and y axes, the PEC and PMC boundaries can be used as the periodic boundary condition for normal incidence case. This boundary condition actually constitutes a PEC-PMC waveguide which supports the plane wave as the fundamental mode with zero cut off frequency. The unit cell structure can be regarded as the microstrip resonator, which is loaded at the termination of the waveguide. The waveguide works as the feeding line for the resonator. The two opposite PEC boundaries are insulated by the two lateral PMC boundaries since they don't conduct electric current, hence the PEC-PMC boundaries can also be regarded as the dual conductor transmission line with a certain characterization impedance. When the unit cell resonates, it exhibits pure resistance to the feeding line, and its total input reactive impedance is zero. By adjusting the size of the microstrip line, and the thickness of the substrate, the resonance frequency can be designed. In order to achieve high absorption, the unit cell outer dimension should be optimized to adjust the effective input resistance exhibited by the microstrip resonator to the waveguide. When the effective input resistance is equal to the characterization impedance of the feeding line, perfect wave absorption is achieved. A varactor is integrated into the microstrip resonator, as shown in Fig. 1(a). Through tuning the bias voltage applied on the varactor, the junction capacitance of the varactor is changed so that the resonance frequency, i.e. the absorbing frequency, can be shifted.

Fig. 2(a) shows the electric field distribution at the *xz* plane. The unit cell can be regarded as two segments of microstrip lines with short circuit termination. They are coupled through the varactor. Under the excitation of the fundamental mode of the PEC-PMC waveguide, i.e. plane wave excitation, the two segments of microstrip line resonate out of phase, as shown in the Fig. 2(a). Hence, the *z* component of the electric field is zero at *yz* plane so that there is a virtual PEC plane at *yz* plane. As a result, the left or right half of the unit cell can be modeled as the circuit depicted in Fig. 2(b). In the X-band, the varactor's parasitic inductance dominates so that the varactor shall be regarded as a tunable inductor. The short-terminated microstrip line exhibits capacitance to the varactor when it is larger than its quarter guided operation wavelength. By optimizing the dimensions of the microstrip line, a proper effective input capacitance of the microstrip line can be obtained, which will resonate with the effective inductance of the varactor at a certain frequency. When the unit cell resonates, it exhibits purely effective input resistance to the feed waveguide, while the total reactive impedance is zero. The resistance originates from the energy ohmic loss in the unit cell. Its value is related to the resonance strength, and can be adjusted by optimizing the unit cell dimensions, such as the unit cell periodicity. In order to achieve efficient absorption, the effective input resistance should match the characteristic impedance of the PEC-PMC waveguide if we regard the PEC-PMC waveguide as a dual conductor transmission line.



(a)

(b)

Fig. 2. (a) Simulated electric field at *xz* plane at the peak absorption frequency. (b) The equivalent circuit of the left or right half of the unit cell.

III. SIMULATIONS AND MEASUREMENTS

Simulations are performed to design and optimize the unit cell using the full wave EM solver based on the finite integration technique. In the simulation setup, the structures are subjected to an incident plane wave. The PEC-PMC boundary conditions are employed. The electric field polarization is along the *x* axis, and magnetic field polarization along the *y* axis. The dielectric substrate is chosen as the FR4 with the permittivity of 4.1, the loss tangent of 0.025 and the thickness of 0.8 mm. The metal on the top and bottom layer are modeled as the copper film with the conductivity of 5.8×10^7 S/m. The size of the unit cell is 16 mm × 10 mm. The width of the central conductor is 8 mm, and the gap where varactor is loaded is 0.4 mm. In simulation, the varactor is modeled as the resistor, inductor and capacitor in series. The capacitance range is from 2.350 pF at 0 V to 0.466 pF at 15 V. The resistor is 2.5 ohm, and the inductor is 1.1 nH.

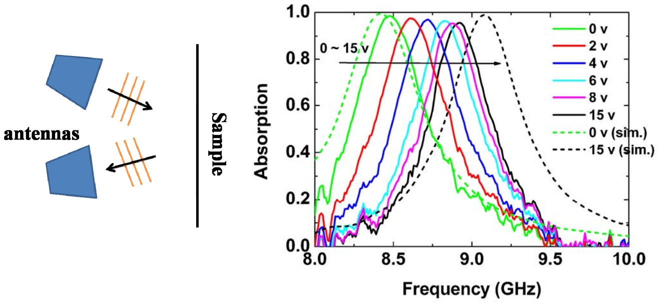
Experiment is also carried out to verify the performance of the proposed tunable absorber. A 210 mm × 244 mm sample board consisting of 20 × 14 unit cells is fabricated using printing circuit board technology, as shown in Fig. 1(b). The SMV1231-011 varactor is used in experiment.

The experiment is performed in the microwave anechoic chambers. Fig. 3(a) shows the schematic of the measurement arrangement. A vector network analyzer (Agilent E8363C) and two horn antennas are used to transmit EM waves onto the sample board and receive the reflected signals. Since the sample absorber has a metallic ground on the bottom layer so that EM transmission is zero, we only measure the reflection coefficient S_{11} of the sample to obtain its absorption, which is calculated as $1 - |S_{11}|^2$. The measurement is calibrated by replacing the sample with the aluminum board of the same size as the perfect reflector (unit reflection).

IV. RESULTS AND DISCUSSION

The measured and simulated absorption for normal incident EM wave at different varactor bias voltage is exhibited in Fig. 3(b).

Tunability of the diode capacitance is achieved by varying the width of its specifically doped P-N junction through the application of the DC bias voltage. Changes in diode capacitance alter the resonant and absorbing frequency of the MA.



(a) (b)

Fig. 3. (a) Schematic of the measurement setup. (b) Simulated (dash) and measured (solid) absorption of the tunable MA at different bias voltage for normal incident EM waves.

When we increases the DC bias voltage from 0.0 V to 15.0 V, the width of the doped P-N junction of the varactor becomes larger and the capacitance becomes smaller, leading to the rise of the absorbing frequency, as shown in Fig. 3(b). When the DC bias voltage is 0.0 V, the measured absorption is 98.3% at 8.48 GHz with a full width at half magnitude (FWHM) of 5%. As increasing the bias voltage, the absorption peak shifts to higher frequencies. At 15.0 V, the frequency of the peak absorption is 8.92 GHz with the absorption rate of 95.2% and the FWHM of 5%. The tuning range of the absorbing frequency is 0.44 GHz.

The peak absorption rate changes slightly as the peak absorbing frequency varies because we optimize the unit cell for the best absorption rate only at one capacitance value. The dash lines in Fig. 3(b) show the simulated absorption at 0.0 V and 15.0 V for comparison. They differ from the measurement results a little bit. This is mainly due to two reasons. First, the varactor parameters used in simulation is measured at the frequency far lower than the X-band, so that the parasitic impedance effect of the diode at high frequency such as X-band is not taken into account. Second, the varactor soldering position may also affect the resonance frequency. However, the agreements are good overall between the experimental results and the numerical simulations.

The resonance mode used in the proposed absorber is the second higher order mode of the unit cell, i.e. microstrip resonator mode. Its fundamental mode is the LC parallel resonance mode which is commonly used in other reported absorber designs [6]. By using the second higher order mode, the unit cell is not much smaller than the working wavelength such that less varactors will be used in the proposed absorber board. If the fundamental LC mode is used to design absorbers in X-band, the physical size of the unit cell have to be very small. This is because the resonance and peak absorption frequency is related to the product of the unit cell inductance and the integrated varactor capacitance. The smallest typical varactor capacitance in market is a few tenths picofarad. Therefore, in order to design high frequency absorber, e.g. in X-band, unit cell shall be small to achieve small structure inductance, which leads to a large number of varactors to be used. However, the frequency tuning range based on the microstrip resonator mode is generally smaller than that based on the fundamental LC mode because the effective input capacitance provided by the microstrip line is dispersive.

Furthermore, the period of the proposed absorber is smaller than the half working wavelength so that the reflected energy concentrates on the specular direction for oblique incidence.

V. CONCLUSION

An active frequency tunable MA is proposed by employing microstrip resonator loaded with varactors. Simulation and experiment have shown that by tuning the bias voltage on the varactors, the absorption peak frequency can be adjusted actively in the X-band. The frequency tuning range is around 0.44 GHz with the peak absorption greater than 95%. Compared with the conventional absorbers based on the LC resonance mode, using the second higher order mode, the unit cell size can be large such that less varactors will be consumed. However, the tuning range gets smaller with this resonance mode. Currently, the proposed design is polarization sensitive. It can be further developed to achieve polarization insensitive EM wave absorbing by using symmetric unit cell structure in the future.

ACKNOWLEDGMENT

This work is partially supported by the National Nature Science Foundation of China (60990322, 60990320, 60801001, 61101011), the Key Grant Project of Ministry of Education of China (313029), the Ph.D. Programs Foundation of Ministry of Education of China (20100091110036, 20120091110032), and Partially supported by Jiangsu Key Laboratory of Advanced Techniques for Manipulating Electromagnetic Waves.

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