Electromagnetic Absorption by Metamaterial Grating System

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Abstract— Total absorption of electromagnetic waves is demonstrated in a system composed of zero-order metamaterial grating and rearward metamaterial wall. The grating and the wall are separated by an air gap. Two mechanisms are shown to account for this absorption. The first one is due to the existence of standing waves in both the grooves of the grating and the air gap. These standing waves trap the electromagnetic waves and induce an oscillating surface charge density on the grating surface. The second one is due to surface plasmons at the interface between the air gap and metamaterial wall, the width of the air gap is a key parameter for the total absorption.

1. INTRODUCTION

Recently, metamaterial is under an intense study due to its potential applications, such as imaging [1], cloaking [2, 3]. In this paper, we will discuss the possibility of using mematerial grating as microwave absorbing structures. It is well known, surface waves can be excited and propagate along the interface between two media with opposite permittivity (or permeability) [4]. The surface wave decays exponentially on either side of the interface, so by carefully choosing the damping factor of the metamaterial, the incident energy can be confined and dissipated. However, surface wave cannot be directly excited by a propagating wave. Usually two methods are used to remedy this, one way is to utilize the attenuated total reflection (ATR) setup [5], the other makes use of diffraction grating [6]. The principle of the two methods is firstly to transform the propagating wave into evanescent one, and then the evanescent wave excites in turn surface waves at interface under proper condition. If another metamaterial is placed behind the grating separated by an air gap, the transformed evanescent wave can then excite surface waves at the interface between the air and the rearward metamaterial, leading to energy dissipation. This principle may provide a new absorption mechanism, so the objective of this paper is to illustrate in detail the interaction mechanism between a metamaterial grating and a metamaterial wall separated by an air gap.
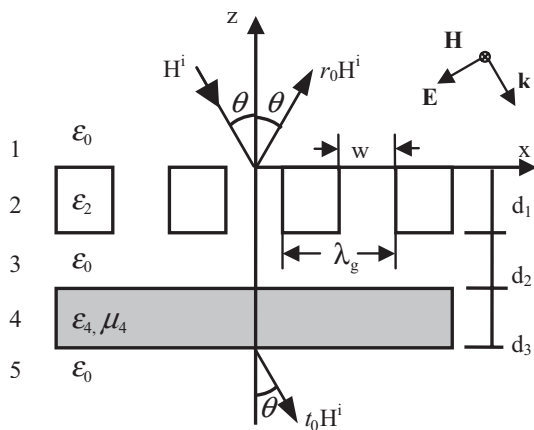

Figure 1: Configuration of the proposed microwave absorbing structure. (1) vacuum, (2) metamaterial diffraction grating, (3) air gap, (4) metamaterial, (5) vacumm.
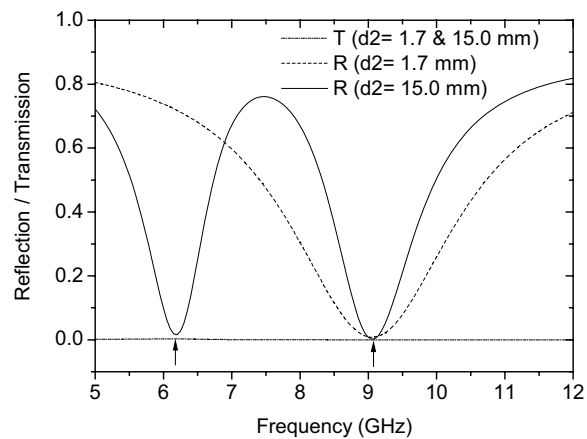

Figure 2: The reflectance and transmittance of the diffraction grating back with a negative permittivity metamaterial for different values of d_2 (i.e., width of the air gap). Total absorptions take place at 6.1 GHz and 9.05 GHz, respectively.

2. REFECTION OF THE FIVE-LAYER GRATING SYSTEM

The sketch of the proposed model is shown in Figure 1, we have a five-layer system. A diffraction grating (layer 2) made of a metamaterial is placed in front of another homogenous metamaterial (layer 4). An air gap separates the grating from the metamaterial. The grating is constructed by

periodically arranging metamaterial strips in vacuum with a period λ_g. The propagating wave is incident to the grating from the upper half space at a random angle θ. For simplicity, the grating vector lies in the x direction, and the normal to the grating plane coincides with z direction, as shown in Figure 1. Basically the metamaterial can be chosen freely, either dielectric or magnetic. As for the p-polarized wave shown in Figure 1, the ridge of the grating is taken to be a metamaterial with a negative dielectric constant, while the metamaterial of the layer 4 can have negative permittivity, negative permeability or both simultaneously (LHM) [7]. To obtain the electromagnetic diffraction properties for the grating structure, the widely recognized rigorous coupled-wave analysis (RCWA) can be used [8], which is highly efficient for the investigation of the binary grating.

Due to the surface plasmon polariton excitation, gratings can exhibit absorption anomalies [9, 10], these gratings are mainly etched on a metal sheet, corresponding to the situation $\varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon_5$ in Figure 1. Since the surface plasmon can only be excited when the incident wavelength equals to the grating period, the bandwidth of the absorption in the frequency spectrum due to surface plasmon are therefore limited. However, the grating can also support the waveguide modes [11–13], in this case, the bandwidth of the absorption can be expected to extend much wider than that due to the surface plasmon mechanism. This may make the grating as an efficient mechanism for microwave absorption.

Figure 2 shows the reflection and transmission curves for two grating structures with different air gaps $d_2 = 1.7$ mm and $d_2 = 15.0$ mm, respectively. We assume $\theta = 0$ in the following analysis, except mentioned else. The material parameters of the grating and the rearward metamaterial are chosen to be nondispersive: $\varepsilon_1 = \varepsilon_3 = \varepsilon_5 = 1$, $\varepsilon_2 = -25.0 + 6.0i$, and $\varepsilon_4 = -1.0 + 0.1i$. The structural parameters are taken as: $\lambda_g = 10.0$ mm, $w = 1.5$ mm, $d_1 = 10.0$ mm, and $d_3 = 30.0$ mm.

It is found that when the air gap is relatively small ($d_2 = 1.7$ mm), the greatest absorption with the minimum reflection appears at 9.05 GHz. At this frequency, no energy is found to travel forward in the region 5, since the transmittance is kept as low as 10^{-5} as compared to the norm of the incident wave. The result also show that the increase of d_3 can even reduce the transmission in the region 5, with little interference to the reflection waves in the region 1. For the air gap $d_2 = 15.0$ mm, two absorption peaks with low transmissions appear at 6.2 GHz and 9.05 GHz, respectively. The reason for these phenomena is due to the formation of wave guide mode in the air gap, this will be explained in detail in the following.

3. ABSORPTION DUE TO WAVEGUIDE MODES

It is shown previously that the width of the air gap is an important parameter to control the reflectance and transmittance properties of the system. Figure 3 gives the variation of reflection as function of the width of the air gap for the incident wave of 6.2 GHz and 9.05 GHz, respectively, the other parameters are kept unchanged. It's interesting to note that the reflectance varies periodically with increasing the width of the air gap. Except the first minimum reflection point, the intervals between the two adjacent minimum reflections equal exactly to the half of the incident wavelength, i.e., 16.6 mm and 24.2 mm for the two considered frequencies, respectively.

Figure 4 shows the variations of $|\mathbf{H}(x, z)|$ as function of x and z over 5 periods of the grating
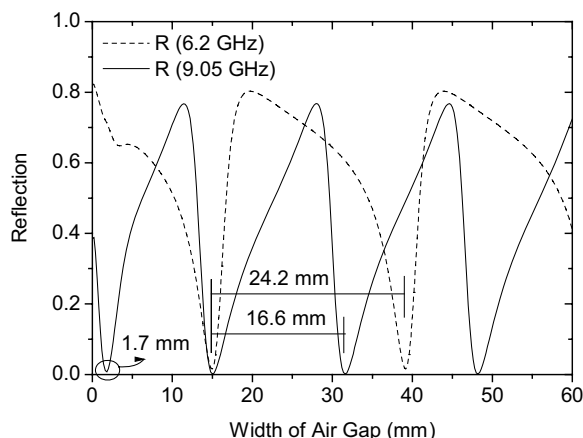

Figure 3: The reflective curves are periodic by increasing the width of the air gap between the diffraction grating and metamaterial.
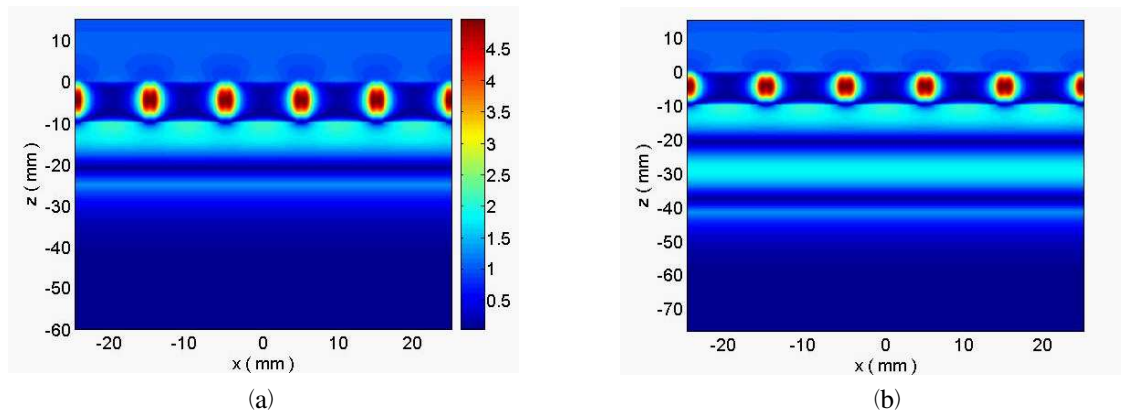
(a)

(b)

Figure 4: (a) Distribution of magnetic field $|\mathbf{H}(x, z)|$ as function of x and z over five pitches of the graiting with $\lambda_g = 10.0$ mm, $d_2 = 15.0$ mm, half wavelength standing wave lies in the air gap, $-25 < z < -10$ mm, (b) $d_2 = 31.6$ mm, a whole period of the standing wave lies in the air gap, $-41.6 < z < -10$ mm.

for the air gap of $d_2 = 15.0$ mm and $d_2 + \lambda_0/2 = 31.6$ mm, corresponding to the second and third minimum reflection points in Figure 3. Where λ_0 is the wavelength for the incident wave, and the incident wave frequency is 9.05 GHz. We found that for these two widths of the air gap, the magnetic field concentrations in the grooves of the different gratings are similar, about 5.5 times higher than the amplitude of the incident field. The concentrated magnetic field will induce a high instantaneous charge density on the surfaces of the grooves, thus greatly enhances the absorbing efficiency [9]. There are also standing waves developed in the air gap for larger air gaps, as shown in Figure 4(a) and (b). The phase delay in Figure 4(b) has π difference compared to the phase delay in Figure 4(a), these explain the intervals between the two adjacent minimum reflections in Figure 3 is exactly the half of the wavelength. As long as the air gap allows the standing waves to form, this means the width of the air gap is probably $n\lambda_0/2$, the air gap works like a vessel with dissipative walls (grating and metamaterial). The dissipation together with absorption in the grooves leads to the minimum reflection shown in Figure 3. Moreover, the formation of standing waves in the air gap (the region 3) is due to the multireflection of the two boundaries of the grating and the rearward metamaterial ($\varepsilon_4 < 0$). If a metamaterial with $\mu_4 < 0$ is used as the rearward wall, it also forbids waves to propagate through, standing waves can also be formed. Figure 5 shows the variation of reflectance as function of the air gap for the frequency 9.05 GHz. The rearward metamaterial is chosen as $\mu_4 = -1.0 + 0.1i$, $\varepsilon_4 = 1$. A notable difference from the result in Figure 3 is that the first two absorption peaks in Figure 5 are well separated by a half wavelength, verifying the condition for the waveguide mode. The first absorption peak in Figure 3 is due largely to the surface resonance at the interface between the air and the metamaterial in case of the p-polarized
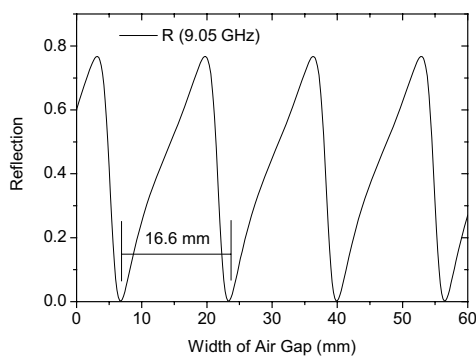

Figure 5: The variation of the reflective curves by increasing of the width of the air gap between the diffraction grating and the metamaterial with a negative permeability, all absorption peaks are due to the formation of standing wave.
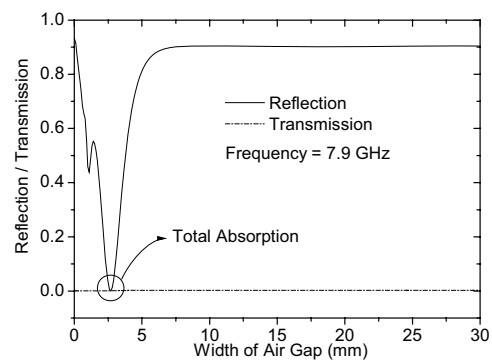
Figure 6: The reflection and transmission at 7.9 GHz for different values of the width of the air gap d_2. While the grating is lossless, total absorption only takes place at $d_2 = 2.7$ mm.

wave. However, the surface wave can not be formed for a rearward metamaterial with $\mu_4 < 0$, so the first absorption peak appeared in Figure 5 is due to the waveguide mode.

4. ABSORPTION DUE TO SURFACE WAVES

Through the waveguide resonance of the grating, the incident propagating wave can be transformed into evanescent one, and then the latter excites surface wave at the interface between the air and the metamaterial under the following relation [5]:

$$\frac{k_{3,\,zm}}{\varepsilon_3} + \frac{k_{4,\,zm}}{\varepsilon_4} = 0. \tag{1}$$

The width of the air gap between the grating and the metamaterial is a critical parameter in this process, this width should ensure the formation of the surface wave at the interface. A slight increase of the width would allow the localized modes to reemit in the forward direction and form propagating waves again [11]. In order to further illustrate this point, a model with a lossless grating and a lossy metamaterial is proposed. We change the material parameters as: $\varepsilon_2 = -25.0$, $\varepsilon_4 = -1.2 + 0.12i$, again the other parameters are kept unchanged. Since in this case only the metamaterial (the region 4) has a damping coefficient, it is the unique part that the incident energy could be absorbed. The reflection as function of the width of the air gap at 7.9 GHz is presented in Figure 6, the frequency 7.9 GHz is chosen here, since without considering the loss of the grating, the minimum refection shifts from 9.05 to 7.9 GHz. As shown in Figure 6, the air gap plays a completely different role, it excites surface waves at the interface between air and the metamaterial instead of setting up standing waves, there is no periodicity at all in the air gap. The reflection peak at $d_2 = 2.7$ mm in Figure 6 corresponds to that at $d_2 = 1.7$ mm in Figure 3 when loss of the grating is not considered. As shown in Figure 7, a clear surface resonance is observed at the interface between the air gap and the metamaterial at $z = -12.7$ mm. Since the grating is lossless, the only role of the grating is to transform the plane waves into evanescent ones without attenuation, so all the incident energy are damped at the interface between the air gap and the metamaterial due to the surface wave.

For the p-polarized illumination, the surface resonance not only can be excited for the case that the metamaterial has a negative permittivity [4], but also can be set up at the interface of air and LHM [5]. By this way, the evanescent wave will penetrate into the LHM and be absorbed if the LHM is lossy. Figure 8 illustrates the reflectance of the diffraction grating with a LHM as the rearward metamaterial for different widths of the air gap. As a reference, the circles represent the reflectance of the diffraction grating ($\varepsilon_2 = -25.0$) without the LHM behind, the transmittance is nearly to 1. When a LHM with $\varepsilon_4 = -10.0 - 2.0i$, $\mu_4 = -1.0 - 0.1i$ is placed behind the grating with a distance $d_2 = 2.5$ mm, the surface waves will be excited at the 8.7 GHz, leading to an absorption peak. Now turning the LHM to be matched with vacuum, i.e., the impedance $Z = \sqrt{\mu_4/\varepsilon_4} = Z_0$ (Z_0 is the impedance of the vacuum), the surface waves will be also induced at 7.5 GHz for the
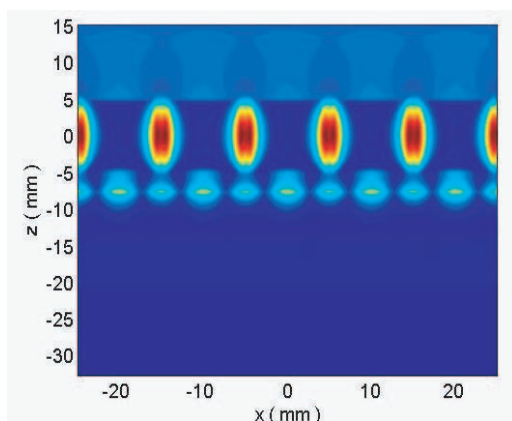

Figure 7: Distribution of magnetic field $|\mathbf{H}(x, z)|$ as function of x and z over five pitches of the graiting with $\lambda_g = 10.0$ mm, $d_2 = 2.7$ mm. Strong surface waves are observed at the interface of $z = -12.7$ mm.
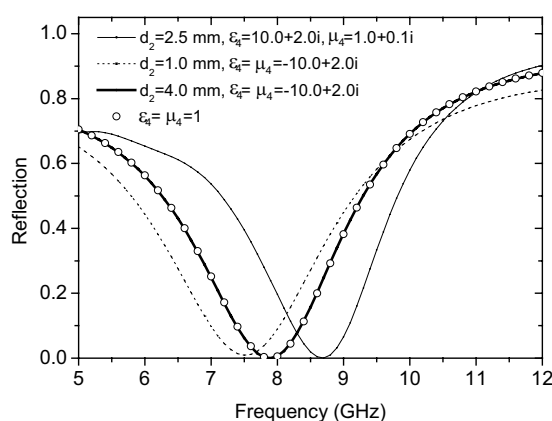
Figure 8: Reflections of diffraction grating back with a LHM at different distances.

distance between the grating $d_2 = 1.0\,\text{mm}$. If this distance is enlarged to a certain value, e.g., $d_2 = 4.0\,\text{mm}$, no surface waves will appear at the interface between the LHM and the air. So the evanescent wave generated by the grating will reemit and penetrate into the LHM. Since a matched LHM can not reflect plane waves, the rearward LHM has no effect on the reflectance or transmittance of the gratings. It is demonstrated clearly in Figure 8 that the thick black line agrees exactly with the reference cycles, implying that the matched LHM has the same role as the air.

5. CONCLUSION

Microwave absorptions are examined for a system of a metamaterial grating and a rearward metamaterial separated by an air gap. It is found that the air gap plays an important role on the absorbing efficiency. While the width of the air gap is relatively small, surface waves can be excited at the interface between the air and the metamaterial, these surface waves are damped along the interface. When the width of air gap becomes large, standing waves can be formed in the air gap. These standing waves together with the high field concentration in the grooves of the grating, can lead to the total dissipation of the incident energy. For the p-polarized illumination, only the materials with negative permittivity or LHM can be used for exciting surface wave. However, the rearward metamaterials with negative permittivity, or negative permeability or both can be used to set up standing waves. This absorption mechanism is expected to have potential application in the microwave absorbing structures.

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