Electrically controlled broadband THz switch based on liquid-crystal-filled multi-layer metallic grating structures

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Abstract. We propose an electrically controlled broadband THz switch based on the liquid-crystal-filled multilayer metallic grating (MMG) structures. During the THz wave passing though the device, it is multiple reflected among the MMG layers and suffers loss due to the absorption of the LC. The on and off state of the switch is realized by the different absorption intensity of the LC when its complex refractive index is switched between ordinary \( n_o \) and extraordinary \( n_e \) value in the presence of an electric field. Simulation results show the proposed device exhibits a respectable switching effect for the THz wave over a wide frequency range.

1. Introduction

Terahertz has been proved greatly potential applications in many domains including imaging, environment monitoring, medical diagnosing and broadband mobile communications [1]. However, until now there are few reports on the commercial THz products, despite the THz generation and detection techniques being available for many years. This is partly due to the lack of components to guide and manipulate THz waves. In the field of building tunable THz devices, the liquid crystal (LC) materials are potentially suitable, as they have relatively large birefringence and low absorption in the THz range [2]. Up to now, several LC-based THz devices have been reported [3-14], such as phase shifters [4-7, 11], filters [14, 15], switches [9, 12] and polarizers [13]. At THz region, the thickness of the LC must be the order of wavelength or longer in order to achieve significant tunable range. However, it is difficult to align the thick LC cell, especially when the thickness is of the order of hundred microns [8, 14]. Although this problem can be overcome by using strong external magnetic fields, it makes them inconvenient for practical use [4, 7]. For a compact design, another approach to control the orientation of the LC is by applying a high electric field. But it is not easy to fabricate the transparency conductive electrodes, as even metal layers as thin as tens of nanometers are almost completely opaque to THz waves. This issue makes it more difficult to design an effective electrical controlled THz device based on LC.

Recently, we proposed an electrically controlled THz switch based on the metallic grating-liquid crystal-metallic grating (MG-LC-MG) structures [16]. The switching mechanism is realized by

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modifying the effective refractive of the LC using different bias electric fields. In this novel design, the MGs not only support the super transmittance at certain frequencies, but also act as the electrodes. Therefore, the proposed device has the potential advantage of avoiding the insertion loss due to the indium tin oxide (ITO) electrodes used in [14, 17]. However, the operate frequencies should be carefully chose at the Fabry-Perot (FP) resonance peaks of the MG-LC-MG structures, that is, it is a narrowband THz switch.

Here, we propose an electrically controlled broadband THz switch based on the liquid-crystal-filled multilayer metallic grating (MMG) structures. During the THz wave passing thought the device, it is multiple reflected among the MMG layers and suffers loss due to the absorption of the LC. The on and off state of the switch is realized by the different absorption intensity of the LC when its complex refractive index is switched between ordinary \( n_o \) and extraordinary \( n_e \) value in the presence of an electric field. Simulation results show the proposed device exhibits a respectable switching effect for the THz wave over a wide frequency range.

2. Theory model and simulation method

Figure 1 shows the schematic diagram of our proposed MMG device. The device comprises multilayer identical MGs parallel to each other with the same spacing (S) filled with liquid crystal. The MG periodicity and the thickness of the metal stripe are \( p = 100 \mu m \) and \( h = 0.32 \mu m \), respectively. The incident THz beam is \( p \)-polarized.

\[
\text{Figure 1. Schematic of the multi-layer metallic grating structures. The spacing of the MGs is filled with LC.}
\]

When the wavelength of the incident THz wave is much greater than the period of the MG, the MG can be regarded as homogeneous lamella. Each MG can provide a long-wavelength reflectance with negligible absorption losses [18]. For the normal incidence, the effective refractive index for the \( p \)-polarized wave is [19]

\[
n_m = \left( \frac{f}{\epsilon_m} + \frac{1-f}{\epsilon_{LC}} \right)^{\frac{1}{2}}
\]

where the fill factor \( f = \frac{a}{p} \) is defined as the ratio of the width of metal stripe \( a \) to the MG period \( p \). \( \epsilon_m \) and \( \epsilon_{LC} \) are the relative permittivity of metal and the LC, respectively. If the spacing \( S \) is sufficiently great, there will no evanescent coupling among the MGs, the proposed device shown in Figure 1 acts as a multilayer mirror. The transmission spectrum exhibit reflection bands around the frequencies:

\[
f_m = \frac{cm}{2n_{LC}S} \quad (m=1,2,3,\ldots)
\]
here, c is the speed of light in vacuum, $n_{LC}$ is the effective refractive index of the LC, which can be switched between its ordinary $n_o$ and extraordinary $n_e$ value in the presence of an electric field. This results in a change of the transmission properties of the multilayer structure.

In order to study the detail transmission characteristics of the device, especially the influence of changing the LC refractive index on the transmission spectra, we carried out rigorous coupled wave analysis (RCWA) method in the in the next section. For simplicity, we simulate the model in 2D space, and the metal stripes are considered infinitely along the horizontal direction. In the calculation, the LC is chosen as 7CB, whose $n_o$ and $n_e$ are approximate to 1.61+i0.028 and 1.73+i0.016, respectively [17]. The relative permittivity of metal is $\epsilon_m = -3 \times 10^4 + i10^5$ [20].

3. Results and discussions

Under the normal incidence, over the frequency range from 0.3THz to 2 THz, the transmission spectra of the $p$-polarized wave for different MG layers and LC refractive indices are shown in Figure 2. In the transmission spectra of the dual-layer MGs structure ($L=2$), large transmission peaks are observed, they correspond to the FP multiple reflections between the two MGs. When the layers of the MG is greater than two, serials of small oscillations arise around the FP resonance peaks, which are equal to the number of the LC layers ($L-1$) in quantity. As the MG layers increases, these small oscillations superimposed together, forming a broad transmission band, as the one seen at the range of 0.5 THz to 0.6 THz in Figure 2(a). The MMG ($L>2$) shows the transmission characteristics of a Bragg structure, narrow reflection bands appear near the frequencies indicated by (2). The width of the reflection band is narrowed with the increasing of the MG layers. For the MMG with eight layers, the width of the reflection bands already reduced to less than 50 GHz.

![Figure 2](image)

Figure 2 Calculated transmissions of the MMG structures versus frequency for different MG layers and refractive indices of LC. The spacing of the MGs is 400 $\mu$m. The width of the metal stripe is 50 $\mu$m.

Comparing Figure 2(a) with Figure 2(b), one can see that the positions of the narrow reflection bands are shifted when the refractive index of the LC changes form $n_e$ to $n_o$. This feature can be used to design a narrow band THz switch. However, the operate frequencies should be accurately chosen in the narrow reflection bands. This may be inconvenient in practical applications. On the other hand, we can notice that the transmission rates of the transmission bands are also strongly influenced. For example, the average transmission rates in the frequency range from 0.5 THz to 0.6 THz shown in Figure 2(a) and Figure 2(b) for $L = 6$ are changed from 0.4 to 0.2. The changing of the transmission rate is mainly due to the different absorption loss of the LC when its imaginary part of the complex refractive index is switched from $\text{Im}(n_e)$ to $\text{Im}(n_o)$. This conclusion can be confirmed by Figure 3. In Figure 3, we plot the transmission spectra of a six-layer MMG structure with the same calculation parameters used in Figure 2, except the absorption of the LC, i.e., the imaginary part of its complex refractive index is neglected. In this case, when the LC refractive index changes, the shift of the
narrow reflection band is still observed, but there is no significant transmittance modulation phenomenon. In addition, the transmission spectra in the range above 1.8 THz show different characteristics, this is because the incident frequency has beyond the diffraction limit, part of the incoming THz beam is coupled into guided mode in the LC layer [21]. Such phenomenon is not seen in Figure 2, as most of the THz wave has been attenuated due to the loss of the LC.

Figure 3. Calculated transmissions of a six-layer MMG structure versus frequency for different refractive indices of LC. The absorption losses of the LC are neglected.

The transmittance modulation phenomenon described above is very suitable to design a broadband THz wave switch. As the modulation mechanism is the result of changes of the LC absorption, the variation of the imaginary part of the LC refractive index is essential. For the LC material 7CB, such value is quite small: $\Delta \text{Im}(n_{LC}) = 0.012$ [17]. In order to obtain more significant modulation effect, it is necessary to increase the THz wave propagate path in the LC. This can be directly achieved by increase the thickness of LC layer. However, it becomes difficult to control the orientation of LC molecules, especially when the thickness is of the order of hundred microns [8]. Another solution is to increase the number of MG layers, as more MG layers means that the THz wave will be reflected more times when passing through the device. We define the extinction ratio $\text{EXT} = 10 \log(T_{ON}/T_{OFF})$, where $T_{ON}$ and $T_{OFF}$ are the transmission rates within the frequency range from 0.5 THz to 0.6 THz in the case of $n_{LC} = n_e$ and $n_{LC} = n_o$, respectively. From Figure 2, it can be seen that the $\text{EXT}$ is approximately increasing from 4 dB to 10 dB when the number of MG layers changes from 4 to 8. If the metal layers continue to increase, it is possible to get a higher $\text{EXT}$. However, this will lead to serious insertion loss (IL). So there is a trade-off between the $\text{EXT}$ and IL.

In certain applications, it is expected that the THz switch can be operated over a broad frequency range. One can easily observe from Figure 2 that the operating bandwidth of the THz switch is affected by the width of the reflection band. Figure 4 shows a comparison of the calculated transmissions of a six-layer MMG structure with different metal strip widths and refractive indices of LC. It is clear that the width of the reflection band can be adjusted by changing the width of metal stripe under the condition of constant MG layers. The reflection band becomes more and more narrow with decreasing width of the metal stripe. When the width of the metal stripe decreased to 20 $\mu$m, the reflection band is almost disappeared in the transmission spectra. In this case, the THz switch can be worked over the whole frequency range shown in Figure 4(a). However, this ideal situation is impossible in practice. In the design of this paper, a bias voltage is applied on the metal stripes of the top and bottom layers of the MGs to provide the electric field to orient the LC molecules along the z-
axis. If the metal stripes are too narrow, the electric field distribution will no longer be quasi-longitudinal. In other words, the reflection of the LC cannot be effectively changed from $n_e$ to $n_o$. As a result, the EXT will become worse. Therefore, there is also a trade-off between the EXT and working bandwidth.

4. Conclusion

In conclusion, we have proposed an electronically controlled broadband THz switch based on the liquid-crystal-filled multilayer metallic grating structures. During the THz wave passing through the device, it is multiple reflected among the metallic grating layers and suffers loss due to the absorption of the LC. The on and off state of the switch is realized by the different absorption intensity of the LC when its complex refractive index is switched between ordinary $n_o$ and extraordinary $n_e$ by external electric field. The relationship between the performance parameters of the THz switch and the device design parameters are studied by RCWA method. Simulation results show that: (1) the extinction ratio is increasing with the number of the metallic grating layers, but accompanying with the deterioration of the insertion loss; (2) a wide operating bandwidth can be obtained with relatively narrow metal strips, however, this will lead to a decline in the extinction ratio. There are trade-off among the extinction ratio, insertion loss and operating bandwidth. As a demonstration, a THz switch using six-layer metallic gratings exhibit a 7 dB extinction ratio and 100 GHz operating bandwidth with an acceptable low insertion loss. Although the switching performance is relatively poor, it is just the simulation results without any further optimization. There is considerable room for performance improvement. Even though there remain challenges to carry out experimental verification, the principle of the device presented here provides a novel strategy to design broadband THz switch.
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