A dual-band amplitude shift-keying terahertz encoder based on 2DEG metamaterial

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Abstract. The amplitude shift keying (ASK) is a significant technique in communications. We propose a terahertz encoder based on the 2-dimensional electron gas (2DEG) metamaterial, which can complete ASK in the 0.43 THz and 0.81 THz independently. The ON/OFF ratio of the encoder in each band is more than 86%. The research is helpful in promoting terahertz technology and next-generation communications.

1. Introduction

Metamaterials are the powerful scheme of controlling electromagnetic waves [1-3], which were developed rapidly in the two decades, especially for the microwave and terahertz devices [4, 5]. To promote the growth of terahertz communications, research on terahertz metamaterial devices is significant. Some current active devices, which are composed of hybrid metamaterials inserted with graphene [6], semiconductor [7], or 2-dimensional electron gas (2DEG) [8], can modulate amplitudes or phases of electromagnetic waves effectively. The signal-bandwidth and transmission rate are key indicators for communications; however, the previous devices were working in a single band, and the bandwidth and efficiency may be insufficient.

In this report, we propose an encoder based on the terahertz metamaterial that can realize dual-band amplitude shift keying (ASK) coding with bias voltage. The encoder consists of the 2DEG-based hybrid metamaterial deposited on sapphire. The device can control the transmission amplitude of the terahertz waves on high (transmitted) or low (non-transmitted) status at 0.43 THz and 0.81 THz independently. We define four codes 00, 01, 10, and 11 as these statuses, which represent the band-windows open or close in different combinations.

2. Design and method

Figure 1 shows the structure of our encoder. The blue part is the substrate, which is sapphire; the metallic structure in yellow is aluminium deposited on the substrate, and the 2DEG structure in brown is heavy doping silicon. Figure 1(a) is the schematic of a unit cell of the hybrid metamaterial: the outer radius of the metallic split-ring resonator (SRR) structure with the gaps is R, the inside radius of metallic structure or the radius of the semiconductor disk is r, the gaps of the metallic ring structure are g, the width of the metallic strip that links contiguous cells is d, the length of the metallic short wire is l, and the periods of the encoder in x and y axes are P. Marked with the red arrows, the thicknesses of metallic structures and semiconductor are t_m and t_s, respectively. The metallic strips on the edges shown in Figure 1(b) are the electrodes connected with the external voltage controller, which is used to control the conductivity of the semiconductor. These structures are deposited on the top and
bottom surfaces of the substrate in different parameters listed in Table 1. As shown in the parameter list, the SRRs on the bottom surface are larger than the SRRs on the top surface, and the period of the array on the bottom surface is twice of the period of the array on the bottom surface.

Figure 1. (a) Schematic of a unit cell of the encoder based on 2DEG metamaterial. (b) Schematic of the whole device in the front view.

Table 1. Parameters of the structures.

| Parameters | Top surface | Bottom surface |
|------------|-------------|----------------|
| R          | 30μm        | 55μm           |
| r          | 25μm        | 45μm           |
| g          | 8μm         | 10μm           |
| d          | 1μm         | 1μm            |
| l          | 8μm         | 11μm           |
| P          | 100μm       | 200μm          |
| t_s        | 0.2μm       | 0.2μm          |
| t_m        | 1.5μm       | 1.5μm          |

We build the models of the encoder in CST Microwave Studio. The boundary conditions in x and y directions are set to be periodic, and the boundaries in z direction are open. The y-polarized terahertz plane waves are normally incident to the top surface of the encoder, and an electric field probe is set to detect the transmission signal. The conductivity of aluminium $\sigma_{Al}$ is $3.56 \times 10^7$ S/m, the permittivities of doping silicon structures and the substrate are $\varepsilon_{Si} = 11.67$ and $\varepsilon_{sub} = 10.9$, respectively. We calculate the conductivity of the doping silicon in different bias voltage with [9]

$$\sigma_{Si} = ne\mu_n + pNe\mu_p,$$

where $e$ is the elementary charge, $N$ is the numbers of the electron hole charge, $\mu_n$ and $\mu_p$ are the mobilities of electron and electron hole, respectively, $n$ and $p$ are the carrier concentrations of semiconductor calculated with

$$\nabla (\varepsilon_{Si} \nabla V) = -q \left( p - n + N^+_D - N^-_A \right),$$

$$\nabla \cdot J_n = -q R_{SRH},$$

$$\nabla \cdot J_p = q R_{SRH}.$$

Here $\varepsilon_{Si}$ is the dielectric permittivity of the silicon, $V$ is the electric potential, $N^+_D$ and $N^-_A$ are the concentrations of ionizing donors and acceptors, respectively. $R_{SRH}$ is the Shockley-Read-Hall, $J_n$ and $J_p$ are the electron and hole currents, which are calculated with

$$J_n = -nq\mu_n \nabla V + \mu_n k_B T \nabla n,$$
\[ J_p = -pq\mu_p \nabla V - \mu_p k_B T \nabla n, \]  
(6)

where \( k_B \) is Boltzmann’s constant, and \( T \) is the absolute temperature. Hence, \( R_{SRH} \) can be calculated with

\[ R_{SRH} = \frac{np - n_i^2}{\tau_p (n + n_i) + \tau_n (p + p_i)}, \]  
(7)

where \( n_i \) is the intrinsic carrier concentration in an undoped semiconductor, \( \tau_n \) and \( \tau_p \) are the carrier lifetimes of electron and electron hole, respectively, and \( n_i \) and \( p_i \) are parameters of the trap energy level.

The carrier concentrations are simulated with the equations above all in COMSOL Multiphysics. Finally, we set the conductivity of doping silicon \( \sigma_{Si} \) from 100 S/m to 90000 S/m.

3. Results and discussion

We simulate the transmission spectrum of the encoder using CST microwave studio with the MW &RF &Optical module in the time domain. The transmission amplitudes of the encoder are shown in Figure 2. There are 4 statuses, 00, 01, 10, and 11, which are shown in Table 2. Here, we define the transmission amplitude as “High” or “Low” depending on whether it is higher or lower than the threshold (chosen as 0.4). The band A and band B are defined as 0.42-0.44 THz and 0.8-0.82 THz, respectively, which are corresponding to the resonance frequencies of the SRRs on the bottom and top surfaces respectively. Note that the resonance dips are broad, in order to guarantee the independent control of two bands, we should adequately separate the working bands.

![Figure 2. Transmission amplitude of the encoder in different states. The shadow areas denote the working bands.](image)

**Table 2.** The encoding status corresponding to the cases of the bias voltage, conductivity of silicon and the transmission.

| Code | Bias Voltage | Conductivity of Silicon | Transmission Amplitude |
|------|--------------|-------------------------|-----------------------|
|      | Top Surface  | Bottom Surface          | Top Surface           | Bottom Surface      | Band A | Band B |
| 00   | 5V           | 5V                      | 100 S/m               | 100 S/m             | Low    | Low    |
| 01   | 5V           | -1V                     | 100 S/m               | 90000 S/m           | Low    | High   |
| 10   | -1V          | 5V                      | 90000 S/m             | 100 S/m             | High   | Low    |
| 11   | -1V          | -1V                     | 90000 S/m             | 90000 S/m           | High   | High   |
The encoding 00 corresponds to the case that both of the bias voltages applied on the two surfaces are 5V, and the silicon is nonconducting ($\sigma_{Si} = 100$ S/m). In this case, the dipole mode is resonant in the metallic structure of each SRR. Since there are two kinds of SRRs on the top and bottom surfaces, they will induce two corresponding resonance dips in the transmission spectrum, hence the transmission of the encoder shows low-transmitted in bands A and B. The encoding 01 corresponds to the case that the voltage of the controller applied on the top surface is 5V, and the bias voltage of the bottom surface is -1V. When the bias voltage is changed to -1V, the conductivity of silicon is increased to 90000 S/m. Thus, the silicon becomes conductive, which breaks the dipole mode, as a result, the resonance dip will be suppressed in the transmission spectrum. Consequently, the transmission of the encoder shows low-transmitted in band A and high-transmitted in band B. The encoding 10 corresponds to the situation that the applied voltages on two surfaces are inverse with status 01, and the transmission in the two bands are inverse too. The encoding 11 corresponds to the case that both of the bias voltages applied on two surfaces are -1V, and the transmission of the encoder shows high-transmitted in the two bands. These 4 states are plotted with the blue solid line (00), green dashed line (01), orange dashed line (10), and red dot-dashed line (11). We calculate the ON/OFF ratio with the difference between the maximum and minimum values divided by the sum of them. As shown in Figure 2, the ON/OFF ratio of the encoder in each band is more than 86%, especially, the ON/OFF ratio in band A can reach as high as 96%.

Figure 2. (a) The top and (b) the bottom views of the sensor. (c) Silicon disk on the top surface with a stripe metallic film. (d) Silicon disk on the bottom surface with a stripe metallic film. (e) The top and (f) the bottom views of the decoder. (g) The left and (h) the right views of the detector. (i) The left and (j) the right views of the repeater. (k) The top and (l) the bottom views of the repeater. (m) The top and (n) the bottom views of the amplifier. (o) The top and (p) the bottom views of the amplifier. (q) The top and (r) the bottom views of the amplifier. (s) The top and (t) the bottom views of the amplifier. (u) The top and (v) the bottom views of the amplifier.

Figure 3. Cross-section views of a unit cell in (a) xoz plane and (b) yoz plane. Carrier concentrations of the silicon disk with different bias voltages in (c) xoz plane and (d) yoz plane.

We also investigate the carrier concentrations in a unit cell using COMSOL Multiphysics. The cross-section views of a unit cell in xoz and yoz planes are shown in Figures 3(a) and 3(b), respectively. The outlines structure is the silicon disk, the yellow and blue parts are aluminum structure and the substrate, respectively. The distributions of carrier concentration of the silicon disk in xoz and yoz planes with different bias voltages are shown in Figures 3(c) and 3(d), respectively. The gray cones show the bias voltage from -1V to 5V with the width change. The rainbow bars show the carrier concentration with the color change. When the voltage is -1 V, the carrier concentration of the semiconductor disk is about 20 cm$^{-3}$ in logarithm. And the distributions of carrier concentration of the semiconductor disk will be changed dramatically when the bias voltage from 1V to 5V. As shown in Figure 3(c), when the bias voltage increases, the carriers are aggregated on the lower left and upper right corners, where are the locations of the voltage apply on the semiconductor disk via the metallic wires. Similarly, with the rise of the bias voltage, the carriers are gathered on the upper and lower.
parts of the structure in Figure 3(d), and the carrier concentration of the rest areas sharply drops to the logarithm level of $10 \text{ cm}^{-3}$. Consequently, the conductivity of semiconductor disk at different bias voltages can be obtained according to the carrier concentration.

Associating with the distributions of current density in the SRRs, we can further demonstrate the resonance principle. The current density of the encoder in the 4 states are shown in Figure 4. Figure 4(a) shows the low-frequency (band A) response of encoder in the state of 00, and the current only distributes on the bigger metal SRRs on the bottom surface, while the small SRRs on the top surface are barely resonant. On the contrary, the high-frequency (band B) response of encoder in the state of 00, as shown in Figure 4(b), is different from the low-frequency response that the current only distributes on the small metal SRRs on the top surface. Figures 4(c) and 4(d) illustrate the low-frequency response and high-frequency response of encoder in the state of 01, respectively. In such cases, the current only distributes on the bigger metal SRRs on the bottom surface. And there are some weak current in the connected places of the structure, which can be attributed to the high-order resonance of the long metal strips. Similarly, Figures 4(e) and 4(f) correspond to the current distribution of state 10, and Figures 4(g) and 4(h) correspond to state 11. It is noted that the low-frequency responses of 10 and 11, as shown in Figures 4(e) and 4(g), show some weak resonance in band A. This phenomenon is attributed to the edge response caused by the blue-shift of the resonance caused by the varying distribution of 2DEG concentration. In addition, tiny residual response in non-resonant state will slightly influence the work efficiency of the structure, but it remains negligible. To sum up, this structure, although in the presence of an edge response, can realize 96% of ON/OFF ratio in band A and 86% in band B, which can accomplish superb coding function.

![Figure 4. The current density of the device resonance in different statuses. (a-b): code 00; (c-d): code 01; (e-f): code 10; (g-h): code 11. The upper/lower column is the current density in band A/B. The arrows denote the directions of the surface currents.](image)

Compared with other researches of terahertz active devices, our encoder has more advantages. The encoder has more states, and it has more bits for communications. The device based on 2DEG can work at a smaller voltage. Besides, since the rising edge signal is shorter, the switching-speed is improved greatly. The ultra-fast switching of the encoder is helpful for improving the encoding rate.

4. Conclusions
We propose a 2DEG metamaterial-based encoding device that can modulate the terahertz waves with ASK in dual-band. The encoder works with the applied bias voltage, which can control the transmission amplitude of the terahertz waves on transmitted or non-transmitted status at 0.43 THz.
and 0.81 THz independently, and the ON/OFF ratio exceeds 86%. This study is helpful in developing terahertz communications and metamaterial-based devices.

Acknowledgment

This work is supported by the Natural Science Foundation of Guangxi Province (Nos. 2018GXNSFAA281163 and 2018GXNSFBA281175), the Science and Technology Program of Guangxi Province (Nos. 2018AD19058, AD18281033) and the Project of Guangxi Education Department (No. 2018KY0213).

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