Abstract. In this paper, the generation and modulation of terahertz wave based on Oxygen-implanted GaAs (GaAs:O) is proposed and discussed. The theoretical analyses and numerical simulation results about the modulation characteristics of the terahertz wave using the proposed scheme have been obtained. Through comparing the numerical simulation results we can find that the information carried on the optical light can be transferred onto the generated terahertz wave and the power of the modulation side bands in terahertz frequency can keep stable in the whole modulation bandwidth. The relationship between the terahertz power and carrier lifetime has also been studied.

1. Introduction

Terahertz wave has numerous benefits, such as high bandwidth, good anti-interference and small antenna size, which make it suitable for short-distance high-speed wireless communications\cite{1-11}. However, the generation and modulation of terahertz wave with high stability and small size is still a big problem need to be resolved for the future terahertz wireless communication systems.

Terahertz photomixer based on low-temperature-grown GaAs (LTG GaAs) is one of the possible solutions for the terahertz genearton with small size and compact structure\cite{10-11}. Compared with LTG GaAs, ion-implanted material not only retains the advantages of high carrier mobility and short carrier lifetime, but also can overcome the temperature sensitivity problem encountered in LTG GaAs growth\cite{1}. So far, many ion-implanted material based terahertz sources were proposed, such as: GaAs:As, GaAs:H, GaAs:N, GaAs:O, InGaAs:Au\cite{2-9}. Among these new materials, the energy level of oxygen ions in GaAs is close to the Fermi level, it makes GaAs:O material almost electrically neutral, and hence a comparatively higher resistance. This property is benefit for signal to noise ratio of the photomixer.

On the other hand, the modulation of terahertz wave is another key problem need to be resolved in the future terahertz communication system. In this paper, two Mach Zender Modulators (MZM) are used as the external modulator to modulate the injected laser light into the photomixer based on oxygen-implanted GaAs (GaAs:O). Theoretical analyses and numerical simulation results about the terahertz modulation have been obtained and presented.

2. Theoretical Analysis and Numerical Simulation
Terahertz photomixing process occurs when the photoconductive device is illuminated by two single mode lasers, which having a frequency differency in terahertz range. Thus the carrier density in the active area will change with the modulation signals when the modulated optical signals are focused onto the photomixer.

The injected instantaneous optical power on the active area can be expressed as:

\[ P_i = P_0[1 + \cos(\Omega t) + \cos(\omega t) + \frac{1}{2}\cos(\omega + \Omega) t + \frac{1}{2}\cos(\omega - \Omega) t] \]  

(1)

Here the \( \omega \) is the frequency difference between the two different optical frequencies corresponding to \( \omega_1, \omega_2 \) respectively. The \( \Omega \) is the modulation frequency applied to the two MZMs. The \( P_0 \) is the power of the optical signals. Thus the change of the photocarrier density in the semiconductor active area can be expressed using the dynamic equation as follows\([10-11]\)

\[ \frac{dn(\omega, t)}{dt} = \frac{\eta_e P}{hfA L} n(\omega, t) \]  

(2)

Where, \( A \) and \( \eta_e \) are the effective active area and the external quantum efficiency, respectively.

The change of the instantaneous value of the carrier density, which can be obtained from the Equation 2, will induce change of the photoconductance of the active area. Thus the photoconductance can be expressed as follows:

\[ G_p = G_0 \left[ 1 + \beta_1 \sin(\alpha t) + \beta_2 \sin(\Omega t) + \beta_3 \sin(\omega + \Omega)t + \beta_4 \sin(\omega - \Omega)t \right] \]  

(3)

where, \( G_0 = \frac{e \mu \eta e N L \tau P_0}{hfA W_e} \), \( \beta_1 = \frac{1}{\sqrt{1 + \tau^2 \omega^2}} \), \( \beta_2 = \frac{1}{\sqrt{1 + \tau^2 \Omega^2}} \), \( \beta_3, 4 = \frac{1}{2\sqrt{1 + \tau^2 (\omega \pm \Omega)^2}} \).

The photoconductance density is an instantaneous value, which will produce a voltage \( v \) across the photogap. The change of the voltage can be described using the following differential equation:

\[ \frac{dv}{dt} = \frac{v_B - v}{R_L C} G_p(\omega, t) \]  

(4)

Generally the generated terahertz wave power can be expressed using the equation of \( P_{\omega} = \frac{v_{ac}^2}{2 R_L} \), where, \( v_{ac} \) is the ac part of \( v \). Under the small signal condition, \( G_0 R_L << 1 \), \( v_B G_0 \) can be regarded as the dc photocurrent \( I_{DC,ph} = v_B G_0 \), thus the power corresponding to the different frequency components of \( \omega, \Omega, \omega + \Omega \) and \( \omega - \Omega \) can be obtained as follows

\[ P_{\omega} = \frac{1}{2} \frac{I_{DC,ph}^2 R_L}{(1 + \tau^2 \omega^2)^2 \left[ 1 + \left( \omega R_L C \right)^2 \right]} \]  

(5)

\[ P_\Omega = \frac{1}{2} \frac{I_{DC,ph}^2 R_L}{(1 + \tau^2 \Omega^2)^2 \left[ 1 + \left( \Omega R_L C \right)^2 \right]} \]  

(6)

\[ P_{\omega - \Omega} = \frac{1}{8} \frac{I_{DC,ph}^2 R_L}{(1 + \tau^2 (\omega - \Omega)^2)^2 \left[ 1 + \left( (\omega - \Omega) R_L C \right)^2 \right]} \]  

(7)

\[ P_{\omega + \Omega} = \frac{1}{8} \frac{I_{DC,ph}^2 R_L}{(1 + \tau^2 (\omega + \Omega)^2)^2 \left[ 1 + \left( (\omega + \Omega) R_L C \right)^2 \right]} \]  

(8)

The frequency components of \( \Omega, \omega + \Omega \) and \( \omega - \Omega \) are present because of the modulation.
In our simulation, the central wavelength of the two input laser beams is assumed to be 850 nm, and the frequency difference between the two wavelengths is 1.0 THz. The photomixer have 10 electrodes, and 9 photogaps, the width of the electrodes and photogaps are 0.2 μm and 1.8 μm, respectively. The length of electrodes and photogaps are both 20 μm. Some other parameters used in the simulation are shown in the following table 1.

| Parameters                  | Symbol | Value          |
|-----------------------------|--------|----------------|
| Central wavelength          | λ      | 850 nm         |
| Power of Laser beams        | P_0    | 40 mW          |
| Internal quantum efficiency | η_s    | 0.8            |
| Bias voltage                | V_B    | 1.5 V          |
| Resistance of antenna       | R_L    | 50 Ω           |
| Coupling capacitor          | C      | 3.0341*10^{-12} F |

Figure 1 shows the simulation results when the modulation rate is 20 GHz and the carrier lifetime is 0.3 ps. When there are no modulation signals applied to the optical modulators, there exist no modulation sidebands near the central frequency. On the other hand, when the modulation signals are applied to the optical modulator, we can find easily that the optical modulation signals have been transferred onto the generated terahertz wave.

Figure 2 shows the results when modulating at the frequencies 40 GHz. It can be seen that the modulation sidebands move away from the central frequency when the modulation frequency increases. What’s more, the generated terahertz wave power kept stable. That’s to say that this modulation method have a very good power stability and can keep the pace of the modulation bandwidth in the optical transport networks.

Figure 3 shows the simulation results about the modulation characteristics for four different materials with different carrier lifetimes 0.2 ps, 0.3 ps, and 0.4 ps. For the four different materials, the simulation results shows that the output power of generated terahertz grows up with the increasing of carrier lifetime. On the other hand, some simulation results of the generated terahertz power to the terahertz frequency are shown in the Figure 4.
3. Conclusion

A highspeed terahertz modulation scheme based on photomixer is proposed and discussed. The optical modulation signals can be easily transferred onto the generated terahertz wave. The terahertz modulation power is quite stable in the whole modulation bandwidth. Further more, the power of the generated modulation signals keeps stable when the modulation rate changes from 20 GHz to 40 GHz. Comparing results of the four kinds of selected material we can find that selecting the bigger lifetime material under meeting the requirements of bandwidth will be good for improving terahertz power.

Acknowledgement

This work was supported in part by the National Natural Science Foundation of China under Grant No.60877059. The authors would like to sincerely thank Mr. Zuan Li and Yinghao Yuan at Huazhong University of Science & Technology, Wuhan, China, for their discussions.

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