Photomixer as a self-oscillating mixer

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Abstract

Photomixing with low-temperature-grown (LTG) GaAs photomixers is known as a promising technique to generate the coherent radiation in the terahertz (THz) range. In principle, the photomixer could also be used for detecting the THz radiation as a tunable heterodyne mixer with an internal local oscillator, and such a self-oscillating mixer would allow us to construct a simple and tunable receiver system without external local oscillator source. According to a simple photoconductor theory, the conversion efficiency and the noise of the LTG-GaAs photomixer receiver are estimated. It is shown that the performance of the photomixer receiver is reasonably high, if the device design is optimized to get a high photoconductivity, and if the device is cooled down to minimize the thermal noise contribution.

1. Introduction

Optical heterodyne mixing (photomixing) in photoconductors (photomixers) with miniature planar antenna has recently become an attractive method to generate the coherent radiation in the THz range. It has been demonstrated that the photomixer offers relatively high efficiency and extremely wide tuning range [1, 2]. The low-temperature-grown (LTG) GaAs is the most widely used material for the photomixing because of its short response time (carrier lifetime) in the sub-picosecond range (τ<1 ps) and relatively high mobility (μ>100 cm^2/V/s). The LTG-GaAs photomixer have already been used for laboratory spectroscopy, and it has been shown that its spectral purity and THz output power are sufficient for such spectroscopic applications [3].

A schematic view of the LTG-GaAs photomixer as a THz source is shown in Fig. 1.

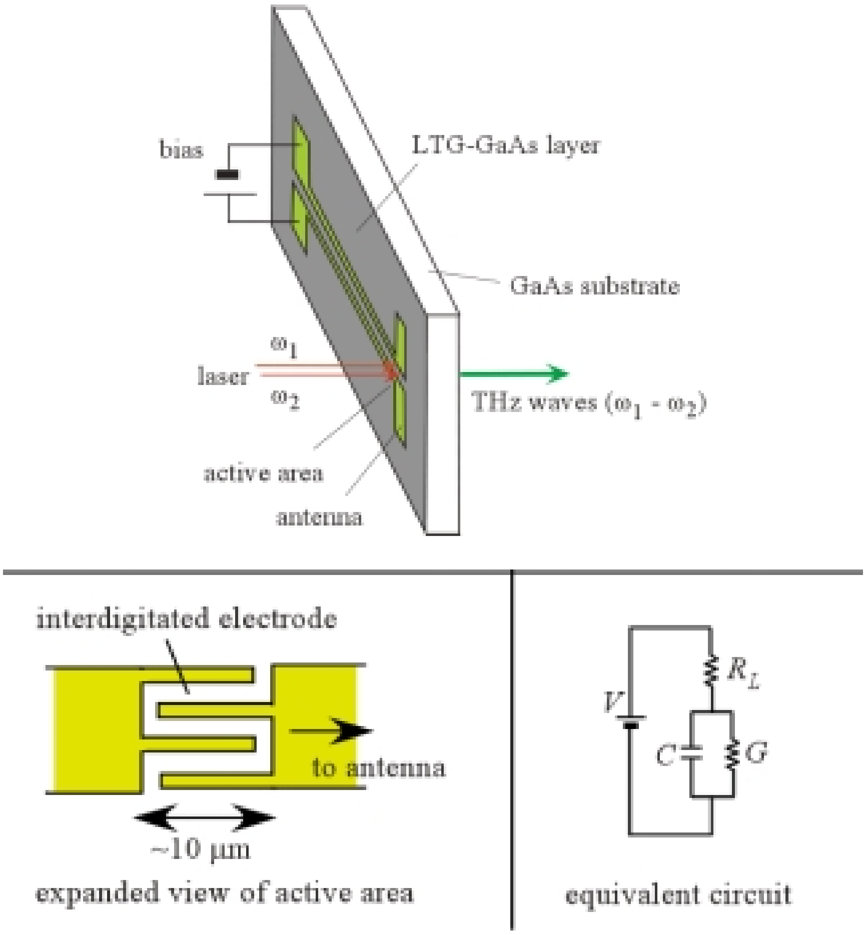

Fig. 1: Schematic view of the photomixer as a THz source.

The active area, consisting of the DC-voltage biased interdigitated electrodes fabricated on the LTG-GaAs layer, is simultaneously illuminated by two single-mode cw lasers at λ850 nm. Beating between the two overlapping laser beams creates a varying optical power at the difference frequency, which modulates the photoconductance. The resultant AC photocurrent is then coupled to a miniature planar antenna patterned on the LTG-GaAs surface. Most of the radiation power goes into the substrate, which has a high dielectric constant (ε=12.8 for GaAs).

According to the reciprocity between transmitting and receiving antenna, the photomixer should be usable not only for the wave generation but also for the detection. The detection principle is the inverse process of the wave generation as illustrated in Fig. 2; small perturbation in the photocurrent induced by the incoming THz field can be measured as the DC current or the IF signal. The LTG-GaAs photomixer receiver has in

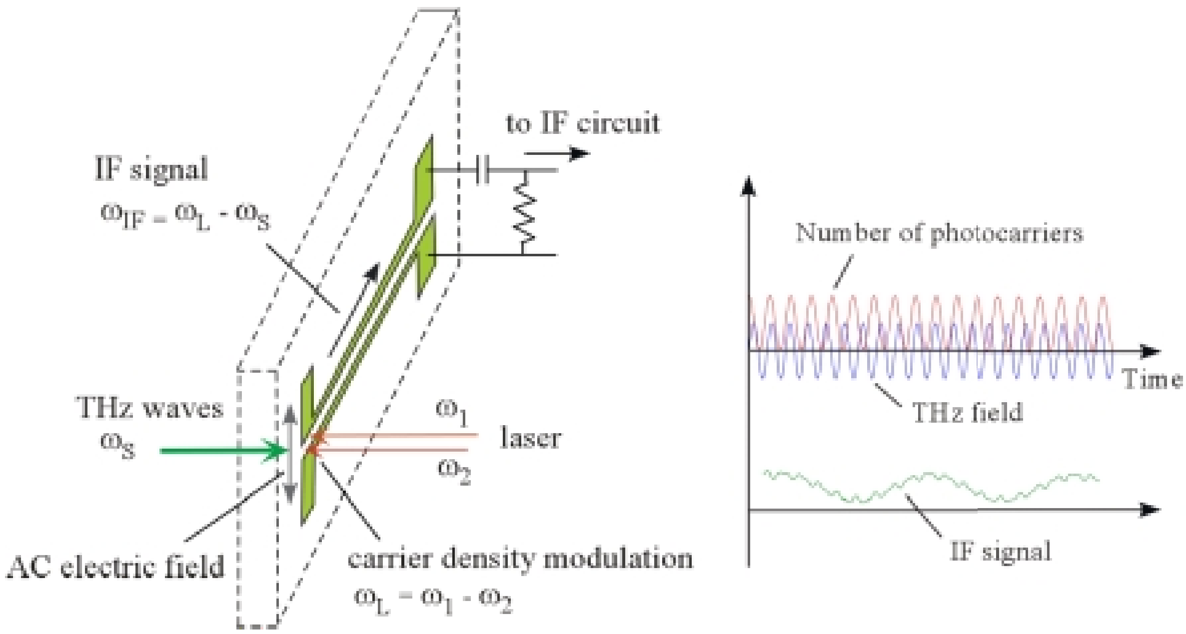

Fig. 2: The principle of the photomixer receiver.

fact been used in the THz homodyne system and has provided high signal-to-noise frequency-domain spectroscopy data even at the room temperature [4, 5].

In principle, the photomixer can be used to detect not only the coherent radiation but also the incoherent radiation as a tunable heterodyne receiver with an internal local oscillator. Such a self-oscillating mixer would allow us to construct a very simple receiver system without external local oscillator. In this paper, the operation of the photomixer as a self-oscillating mixer is proposed, and its performance, the conversion efficiency and the noise temperature, is estimated for the LTG-GaAs photomixer.

2. Photomixer operation in heterodyne mixer mode

The principle of wave detection by the photomixer is regarded as the inverse process of the wave generation by photomixing as illustrated in Fig. 2. When the THz radiation is externally injected to the photomixer whose active area is illuminated by two lasers, the THz field induces the AC bias voltage to the electrode via the antenna. If the temporal change of the photoconductivity at the difference frequency of the two lasers coincides with the external THz field in phase, the rectification of the THz waves takes place, and then the DC current is generated. In the case that the difference frequency is different from that of the incident THz waves, the intermediate frequency (IF) current signal instead of the DC current should be generated. The IF signal is transmitted to the post-mixer amplifier the same as conventional heterodyne mixers. The photomixer should be operated at zero-bias or minimum DC current in order to minimize the current noise as discussed later, in contrast that for the emitter higher bias voltage is required to obtain higher photocurrent.

The photocurrent induced by the electric field, *E*, is given by

$$I = \frac{ne\mu E}{l} = GV \ , \tag{1}$$

where μ is the mobility, l is the gap size of the interdigitated electrodes, G is the photoconductivity, and V is the voltage corresponding to $E=V/l$. The photoconductivity modulated at the difference frequency of the two lasers, $\omega_L = \omega_1 - \omega_2$, is expressed as

$$G = G_0 \left(1 + \frac{\sin \omega_L t}{\sqrt{1 + (\omega_L \tau)^2}} \right), \tag{2}$$

where

$$G_0 = \frac{\eta P_L \tau}{h\nu} \cdot \frac{e\mu}{l^2} \ , \tag{3}$$

τ is the carrier lifetime of the photomixer material, η is the external quantum efficiency of the photomixer, and P_L is the total input laser power. The initial phase of the oscillation is set to be zero. The AC bias voltage induced by the THz field, $V = V_0 \sin(\omega_S t + \phi)$, and the temporal change of the photoconductivity induced by the laser beating create the photocurrent at the intermediate frequency (IF), $\omega_{IF} = \omega_L - \omega_S$,

$$I_{Ph} = \frac{G_0 V_0 \cos(\omega_{IF} t - \phi)}{\sqrt{1 + (\omega_L \tau)^2} \sqrt{1 + (\omega_L R_A C)^2}} \ , \tag{4}$$

where the second term of the denominator represents the roll-off due to the device time constant; R_A is the antenna impedance, and C is the electrode capacitance. If the bandwidth of the IF circuit is sufficiently wide compared with the reciprocal of the coherence time of the input THz radiation, the amplitude of the IF signal power should be comparable to that for the coherent radiation.

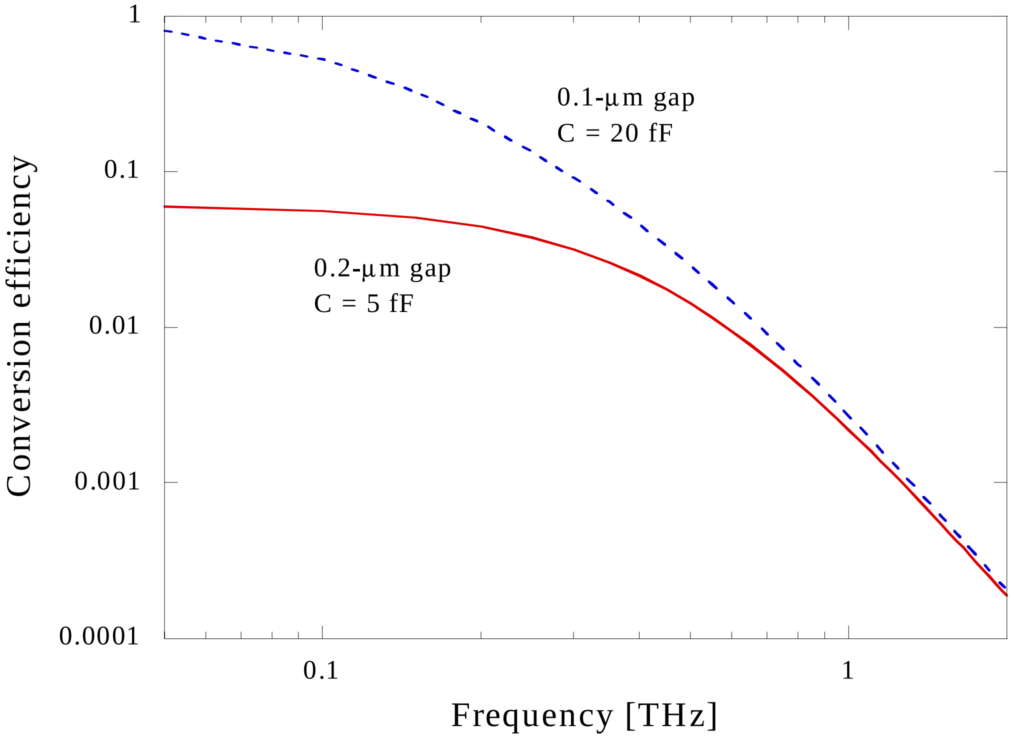

Fig. 3: The conversion efficiency of the photomixer receiver. The solid and dashed curves represent the estimation for the self-complimentary broadband antenna (R_A=72 Ω) device with 0.2-μm and 0.1-μm gap electrodes, respectively.

3. Conversion efficiency

When the THz radiation is injected to the photomixer, the induced voltage across the electrode gaps is

$$V_0 = \sqrt{2P_S R_A}\ , \qquad (5)$$

where P_S is the injected THz power, and R_A is the antenna impedance. The average power delivered to the IF load is given by

$$P_{IF} = \overline{I_{Ph}{}^2} Z_L\ . \qquad (6)$$

From Equations 4, 5 and 6, the conversion efficiency is obtained as

$$\Gamma \equiv \frac{P_{IF}}{P_S} = \frac{G_0{}^2 R_A Z_L}{[1+(\omega_L \tau)^2][1+(\omega_L R_A C)^2]}. \quad (7)$$

From Equations 3 and 7, it is clear that the conversion efficiency can be greatly improved by narrowing the electrode gaps ($\Gamma \propto l^{-4}$).

By substituting the parameters for the LTG-GaAs photomixer into above equations; η = 1, P_L = 40 mW, τ = 0.3 ps, μ = 200 cm^2/V/s, R_A = 72 Ω for the self-complimentary antenna on GaAs, Z_L = 50 Ω, and 20 interdigitated electrodes with the width of 0.2 µm and 19 gaps with l = 0.2 µm (C = 5 fF) [6], the conversion efficiency is calculated to be about 6% at DC. The frequency dependence of the conversion efficiency is shown in Fig. 3. Although these efficiency values are much lower than that for superconducting mixers, they are still in a useful range.

4. Mixer noise

There are several possible noise sources in the photomixer receiver, photocurrent fluctuation and Johnson noise. The current fluctuation due to the random process of generation and recombination of the photocarriers in the photoconductor is known as the G-R noise. The current fluctuation due to the G-R noise in the IF bandwidth of Δf is given by

$$\overline{I_{GR}{}^2} = 4\overline{I_{Ph}{}^2} \cdot \frac{h\nu}{\eta P_L} \cdot \Delta f \, . \quad (8)$$

It is assumed that the photomixer is operated at zero-bias field and that only the AC bias induced by the THz radiation is applied. The signal-to-noise power ratio is

$$\frac{S}{N} = \frac{P_{IF}}{P_{GR}} = \frac{\eta P_L}{4h\nu\Delta f}. \quad (9)$$

The G-R noise limited S/N depends only on the input laser power but the incident THz power. Once the input laser power is set, the S/N cannot exceed this value, even if the THz signal is very strong compared with the other noise. The situation is similar to that the quantization noise of the A/D converter limits the maximum S/N. For the laser power of 40 mW and the bandwidth of 1 GHz, the S/N is higher than 10^7. Therefore, in most cases, this noise should not limit the minimum detectable THz power.

For real setup, it would not be very easy to obtain the perfect zero bias condition, because the electrode contact may not be ohmic and the photovoltaic effect may occur in the device [5]. If the DC electric field ($V_{DC} = l\,E_{DC}$) exists, the minimum detectable power (MDP) is calculated as

$$MDP_{GR} = \frac{2h\nu V_{DC}^{\;2}}{\eta P_L R_A} \cdot \Delta f \;. \tag{10}$$

If P_L=40 mW and V_{DC}=0.1 V are assumed, the mixer noise temperature limited by the photocurrent noise is T_M~70 K. Since the assumed DC field is close to the maximum available value for LTG-GaAs, in most cases this noise level would be close to the upper limit and small compared with thermal noise described as follows.

Thermal fluctuation of the photoconductivity, the laser power fluctuation, and the background photon noise are also possible noise sources, and their noise levels should be similar to the photocurrent noise estimated here.

At relatively high temperature, Johnson noise contributes to the photomixer noise. For the parameter used before, the resistance of the photomixer, R=1/G_0, is approximately 240 Ω. The noise current is given by

$$\overline{I_J^{\;2}} = \frac{4kT}{R} \cdot \Delta f = 4kTG_0\Delta f \;, \tag{11}$$

and the MDP is

$$MDP_J = \frac{2kT}{G_0 R_A} \cdot \Delta f \;. \tag{12}$$

When the photomixer is operated at the room temperature (T=290 K), the active area is locally heated up by the laser to T~190 K [2], and the mixer noise temperature is T_M~1300 K at low frequency limit.

5. Possible improvement

The conversion efficiency could be improved by using the photomixer material with longer carrier lifetime, in particular at lower frequencies. Even at higher frequencies the efficiency may become better by increasing the carrier lifetime, because the mobility may also increase with increasing the carrier lifetime. Same argument should be concluded for the photomixer THz source, but we have actually used the LTG-GaAs with the shortest carrier lifetime by the following reason. When the material with much longer carrier lifetime is used, the AC current oscillating at the THz frequency is a small fraction in the total photocurrent, and it may be easily destructed by the random fluctuation of the

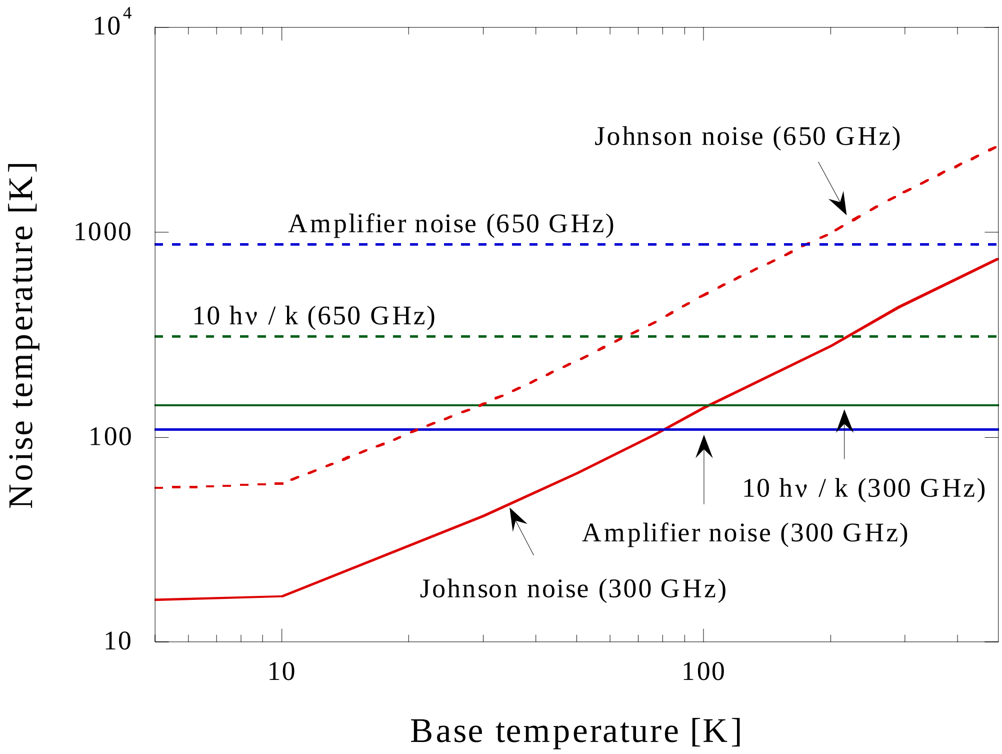

Fig. 4: The noise temperature for the 0.1-μm gap device at 300 GHz and 650 GHz as functions of the ambient temperature. The noise contribution from the post-mixer amplifier, $\Gamma^{-1}T_A$, for T_A=10 K and the quantum noise limit $10h\nu/k$ are also indicated.

DC photocurrent. The optimum carrier lifetime for the receiver may be much longer than that for the source, because it is operated at the zero bias, which the photocurrent fluctuation is small.

As shown before, the conversion efficiency is highly dependant on the electrode gap. The conversion efficiency of the device with 0.1-μm wide and 0.1-μm gap electrodes and with the same active area as the 0.2-μm gap device is shown in Fig. 3. This device shows great improvement in the efficiency at lower frequencies but not much at higher frequencies because of its large capacitance, C=20 fF. If the resonant antenna device is used, the capacitive part of the antenna impedance can be canceled out, and then high efficiency can be achieved at a certain frequency. The traveling-wave photomixer has also potential to overcome the RC-limited bandwidth problem, and it would offer better efficiency at higher frequencies [7].

If the photomixer is cooled down to the liquid nitrogen temperature, the temperature of the active area becomes T=90 K [2], and the Johnson-noise-limited noise temperature for the 0.1-μm wide gap device becomes T_M~100 K at the low frequency limit. Shown in Fig. 4 is the noise temperature of the 0.1-μm wide gap device operated at 300 GHz and 650 GHz as functions of the base (ambient) temperature. According to the conversion efficiency shown in Fig. 3, the contribution of the post-mixer amplifier noise of T_A=10 K to the mixer noise, $\Gamma^{-1}T_A$, is also shown in Fig. 4. The mixer noise temperature of the photomixer receiver can approach to the quantum limit, if the device is cooled down to the liquid nitrogen temperature. Cooling the device should be also helpful to improve the conversion efficiency, because the carrier mobility increases with decreasing the temperature.

6. Conclusion

The idea on the use of the photomixer as a self-oscillating mixer (receiver) was presented. By assuming the use of the LTG-GaAs photomixer with sub-μm electrode structure, the conversion efficiency and the noise were estimated. The conversion efficiency of the photomixer receiver is low, and the post-mixer amplifier would limit the receiver noise temperature especially at higher frequencies, but the sensitivity would be still in a useful range for some applications. The improvement of the photoconductivity by narrowing the electrode gap is crucial for the improvement of the conversion efficiency and the reduction of the mixer noise. At the room temperature, the thermal (Johnson) noise dominates in the mixer noise. Therefore, the mixer noise can be greatly reduced by cooling the device. The experimental study to prove the principle is in progress.

If the device works as is expected, it allows us to construct a very compact, highly tunable, heterodyne receiver system without external LO source. Although its sensitivity is not very high compared with present-day fixed-tuned superconducting mixers, its overwhelmingly wide frequency tunability should be useful especially for space-based remote sensing applications. It is also worthy to note that the THz-wave detection technique presented here is quite general and applicable to not only the LTG-GaAs photomixer but the other types of photomixers, e.g. ultra-fast PIN photodiodes.

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