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A Photonic Local Oscillator Source for Far-IR and Sub-mm Heterodyne Receivers

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Abstract: We presented a recently developed compact solid-state far-infrared and sub-mm (terahertz) source. The radiation is generated by the optical heterodyne conversion (photomixing) in a low-temperature-grown GaAs (LTG-GaAs) photoconductor with a sub-picosecond response time. In photomixing, two frequency-offset laser beams are used to illuminate the photoconductor, resulting in the photocurrent oscillation at the difference frequency that drives a planar antenna on the device. Such a photonic source has the great advantage of compactness, wide tuning range and high efficiency over existing electronic devices, and would be suitable for use as local oscillators in heterodyne receivers for IR/sub-mm astronomy.

1. INTRODUCTION

Many molecules have a rich spectrum of vibrational and rotational transitions that lie in the far infrared and sub-mm or terahertz (THz) region and exploring molecular species in interstellar space by measuring these molecular lines is an important subject of molecular astrophysics. In such high-resolution spectroscopic measurements, heterodyne receivers have the advantage of high sensitivity over direct detectors, but lack of a simple and compact THz source as a local oscillator (LO) has hindered the development of heterodyne observation in this region. Sources exist in this region based on molecular lasers or electron tube devices, but they are generally bulky, complicated, consume large amounts of power and oscillate in restricted frequency ranges. At present, the most successful LO technology in the range of 0.2-1 THz is harmonic generation using Schottky diode multipliers and Gunn master oscillators that

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operate near 100 GHz. At higher frequencies above 1 THz, the multiplier sources suffer from low conversion efficiency and narrow tuning range.

Optical heterodyne mixing (photomixing) in voltage biased low-temperature-grown (LTG) GaAs photoconductors (photomixers) with miniature planar antennas has recently become an attractive frequency down-conversion method because it has demonstrated a relatively high conversion efficiency (Brown, Smith, & McIntosh 1993; Brown et al. 1995). An advantage of the difference frequency generation over the harmonic generation is its extremely wide tuning range. Diode-laser-based systems are particularly promising in this type of application since they combine low power consumption and long lifetime in an inexpensive and compact package (McIntosh et al. 1995; Matsuura, Tani, & Sakai 1997). Such systems have already been applied to laboratory spectroscopy by several authors (Pine et al. 1996; Chen et al. 1997; Matsuura et al. 1998), and it has been shown that the spectral purity and the tuning range of the THz output are sufficient to be used as a local oscillator in a heterodyne receiver, though the output power, at present, is not sufficient to drive heterodyne mixers.

In this paper, we present basic properties of the photomixer and then we describe the prototype of the photomixer LO source to demonstrate its high performance as a spectroscopic tool. Finally, we discuss about the future direction of the photomixer effort in terms of the output power improvement, describing a new device design.

2. PHOTOMIXING

The basic photomixer structure is illustrated in Figure 1. The active area, consisting of voltage biased interdigitated metal electrodes on a LTG-GaAs layer, is simultaneously illuminated by two single mode cw lasers. Typical values for the gap size between the interdigitated electrode fingers and for the total active area are about 1 μm and 100 μm^2, respectively. Beating between the two overlapping laser beams creates a varying optical power at the difference frequency, which modulates the photoconductance. The resulting AC photocurrent is then coupled to a miniature planar antenna patterned on the LTG-GaAs surface. Most of the radiation from the antenna is emitted into the substrate since it has a high dielectric constant ($\varepsilon = 12.8$ for GaAs). A high resistivity silicon lens is attached to the backside of the substrate to collimate the output beam.

The LTG-GaAs is the most widely used ultrafast photoconductor with a response time (carrier lifetime) in the sub-picosecond range ($\tau < 1ps$). The carrier lifetime of the photoconductor material is a crucial parameter for device performance as a THz source. In the case that the difference frequency between the two lasers is higher than $1/\tau$, the AC photocurrent in the photomixer is greatly suppressed. The LTG-GaAs has relatively high mobility, which is also essential to provide high photoconductivity, compared to the other ultrafast photoconductors.

An equivalent circuit diagram for the photomixer is shown in Figure 1. The active region of the photomixer is represented by a resistive element with a conductance G. The antenna is represented by a resistive load with a resistance R_L, although general antenna designs may have a complex impedance. A capacitance, C, depends on the geometry of the interdigitated fingers in the active area. Coupling between the capacitance and the antenna impedance causes additional high frequency roll-off in the output power spectrum. Typical values for the capacitance range from about 0.5 fF to several fF, and the roll-off by the RC time constant appears in the THz range.

According to a simple photoconductor model (Brown et al. 1995), the output power at the difference frequency can be written as,

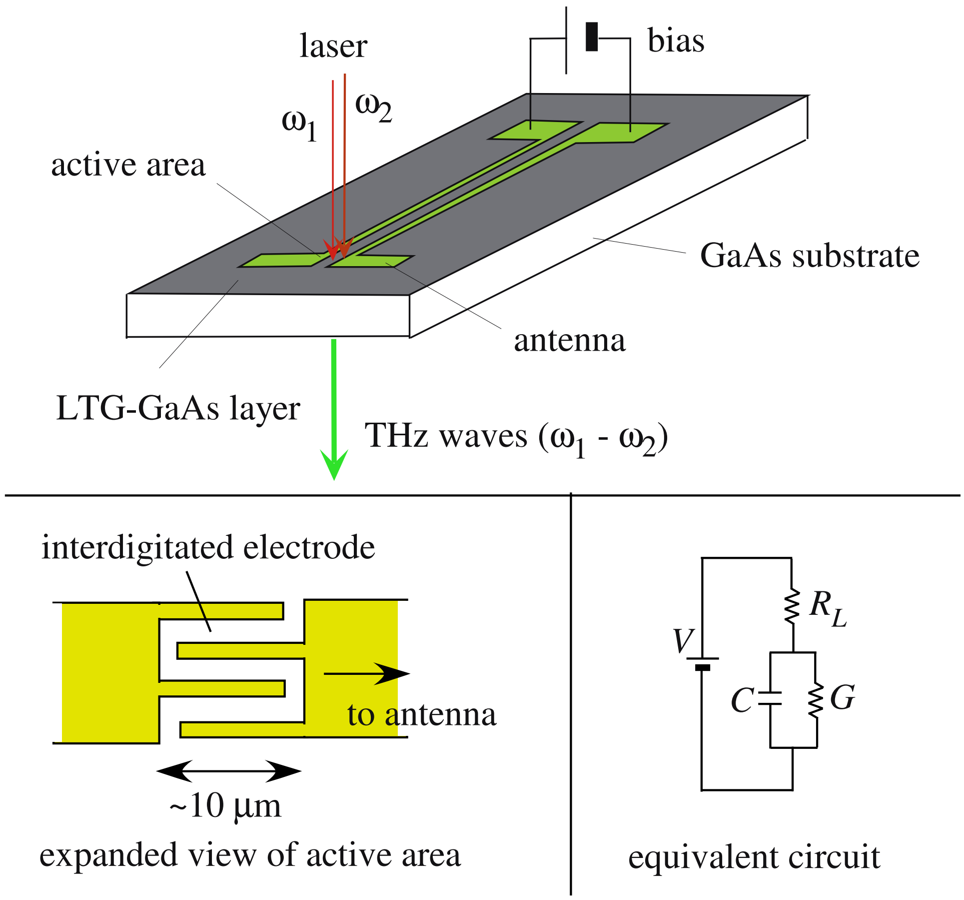

Fig. 1: The basic photomixer structure.

$$P_\omega = \frac{I_1 I_2 R_L}{2[1+(\omega\tau)^2][1+(\omega RC)^2]} \ ,$$

where I_1 and I_2 are the DC photocurrents from each of the two pump lasers. The frequency roll-off terms arise from a finite carrier lifetime of the photoconductor material and from the RC time constant. This equation is valid for the small signal regime where $R \ll G^{-1}$. The output power scales with the square of the photocurrent, and the smaller electrode capacitance will be the wider bandwidth. The output spectrum for a photomixer with a frequency independent log-spiral antenna ($R_L = 72\Omega$) is indicated by the dashed curve in Figure 2. The spectrum shows the high-frequency roll-off of 12 dB/Oct as is expected from the equation.

3. FREQUENCY CONTROL AND STABILIZATION

Frequency stability of the photomixer output is a key issue for the LO source application. In the difference frequency generation, the frequency stability of the output is basically determined by the stability of the pump lasers. Most of our photomixer measurements have been made using single-mode external-cavity diode lasers at $\lambda \sim$850 nm, which provide the spectral purity of the difference frequency better than 1 MHz (Matsuura et al. 2000), while the linewidth of

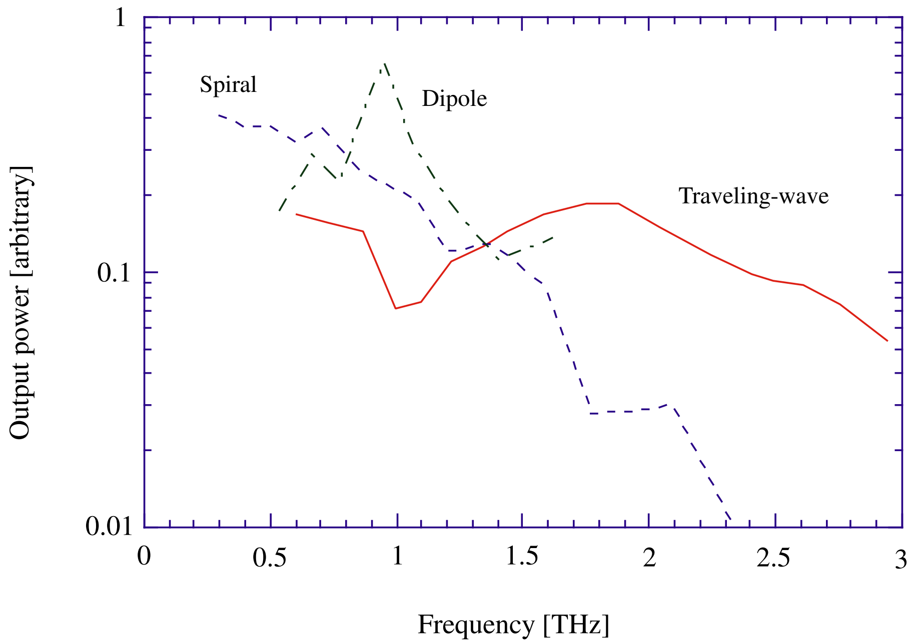

Fig. 2: The output power spectra from the various type of photomixers. The dashed, dash-dotted and solid curves represent the log-spiral, dipole and traveling-wave devices, respectively.

free-running diode lasers ranges roughly from a few MHz to several tens MHz.

Shown in Figure 3 is an example of the frequency stabilized laser system that we used for the photomixer measurements. In this system three diode lasers are used to synthesize a precise difference frequency maintaining the advantage of the wide tuning ranges of diode lasers. Frequency control is achieved by locking two of the lasers (#1 and #2) to different longitudinal modes of an ultra-low-expansion (ULE) Fabry-Perot (FP) cavity. The difference frequency between the two cavity-locked lasers is discretely tunable in steps of the free spectral range (FSR). The third laser (#3) is heterodyne phase-locked to one of the cavity-locked lasers (#2) with a tunable 3-6 GHz microwave synthesizer. The difference frequency between the #1 and #3 is determined by the sum of integral multiples of the FSR (3 GHz in the present system) of the reference cavity and the microwave offset frequency. The accuracy of the difference frequency is determined by the accuracy of the FSR measurement along with any DC offset in the electrical portions of the lock loops. The microwave offset frequency is locked to a high accuracy (1 in 10^{-12}) reference source. The ULE material has a thermal expansion coefficient at room temperature of $\alpha = -2 \times 10^{-10} C^{-1}$, which is comparable to the stability of a good quartz reference oscillator in conventional microwave sources.

All the optical signal processing components of the present three laser system are implemented in polarization-maintaining (PM) single-mode fiber. Due to the insertion losses of the fiber, the output power was insufficient to optimally pump the photomixer used to generate THz-waves. As a result, a semiconductor optical amplifier was employed as the final optical element before the photomixer (Matsuura et al. 2000). The available maximum output power of previous diode laser sources for photomixing were less than 100 mW, while the present system with the optical amplifier provides 500 mW output. Unfortunately, since the maximum pump laser power which the small active area LTG-GaAs photomixers used in this study can handle is

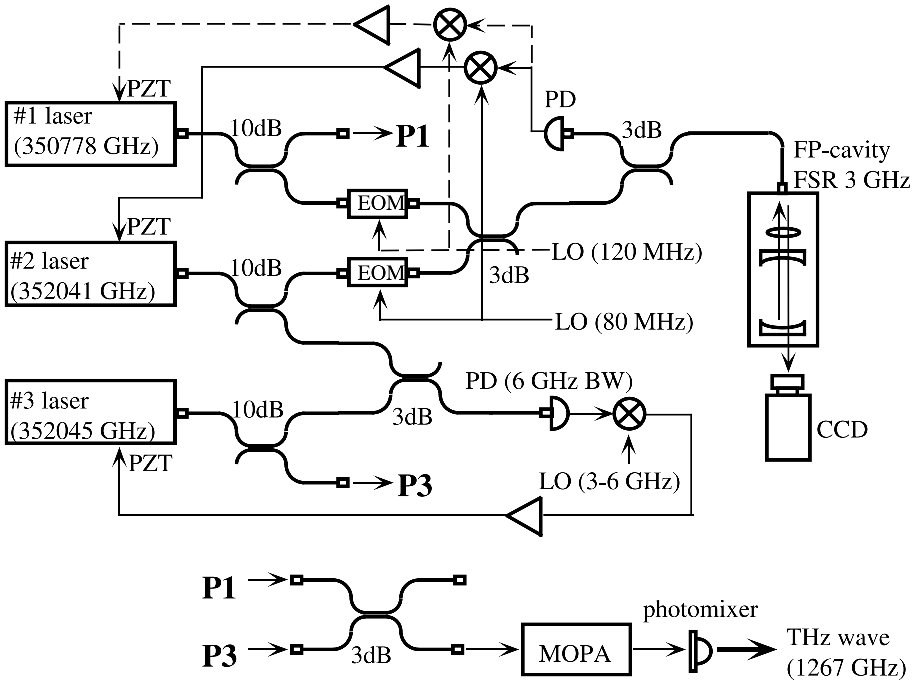

Fig. 3: Schematic diagram of the three diode laser system that synthesizes a precise difference frequency. The indicated laser frequencies represent the actual values to generate the THz wave at 1.267 THz.

limited to approximately 50 mW by their thermal failure (Verghese, McIntosh, & Brown 1997), we had to attenuate the amplifier output appropriately.

4. SPECTROSCOPY

Due to the lack of spectral analysis techniques in the THz region, spectroscopic measurements provide one of the best diagnosis of frequency and spectral purity, which are essential if this source is going to be useful as a local oscillator. In order to prove the performance of the three-laser system, we have performed high-resolution rotational spectroscopy of simple molecules such as acetonitrile (CH_3CN) and carbon monoxide (CO).

The LTG-GaAs photomixer used in the spectroscopy was grown on a semi-insulating GaAs substrate, and a planar log-spiral antenna with 0.2-μm interdigitated electrodes and 1.8-μm gaps in a 8×8 μm active area was etched on the wafer (Verghese, McIntosh, & Brown 1997). A DC bias voltage of 20 V was applied to the electrodes by a constant current supply set at 0.5 mA. The pump laser power was attenuated to 30 mW in order to keep the input power to the photomixer well below the thermal failure threshold. Under these conditions, the photomixer provided a maximum output power of ~ 0.1 μW at 1 THz, which is similar to the values obtained in previous reports. The spectral bandwidth of the generated THz-waves was approximately 700 GHz, in accordance with the carrier lifetime of the LTG-GaAs of $\tau \sim 200$–300 fs and the photomixer RC time constant, where $R_L = 72\Omega$ is the radiation impedance and $C = 0.5$fF is the electrode capacitance (Verghese, McIntosh, & Brown 1997). The FM modulation method with a silicon bolometer was used to obtain the second derivative absorption spectra of molecules.

Shown in Figure 4 is the absorption spectrum of the CH_3CN $J_K = 16_K \to 17_K$ rotational transitions near 312 GHz. The spectrum shows the well known K-structure of a symmetric-top, with K components from K = 0-11 assigned in the spectrum. The K = 0, 1 lines, which are separated by ~6 MHz, are clearly resolved. The gas pressure was 60 mTorr, and the observed line widths are consistent with a convolution of pressure broadened linewidths and the instrument response. The result indicate that the spectral purity and frequency control of the THz source system is sufficient for the laboratory spectroscopic study of molecules at THz frequencies, as well as many local oscillator applications.

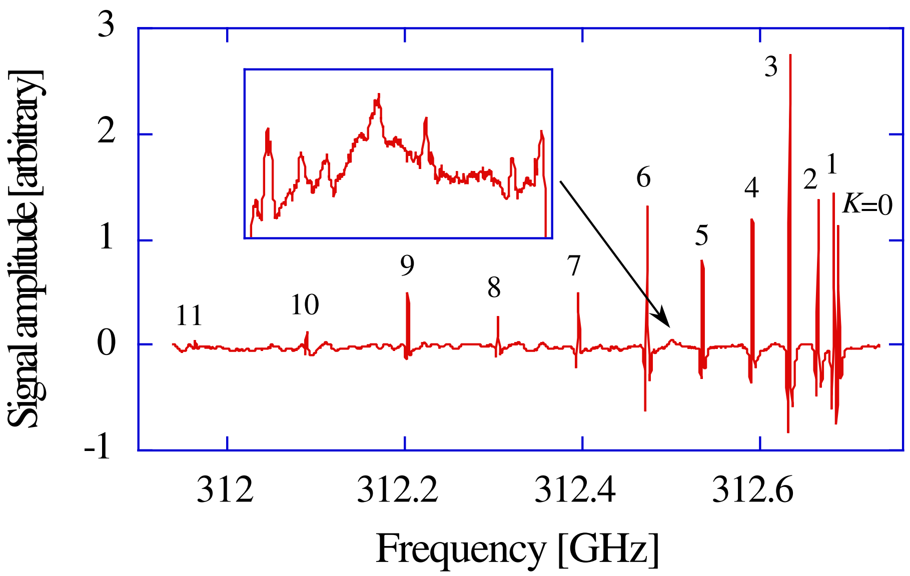

Fig. 4: The second-derivative absorption spectrum of CH_3CN $J_K = 16_K \to 17_K$ rotational transitions near 312 GHz. The inset is expanded view of the ^{13}C isotopic features.

For further spectroscopic measurements such as the search for unknown molecular lines and for use in astronomical observations, absolute frequency calibration of the difference frequency is necessary. Since the accuracy of the difference frequency is defined by the reference FP-cavity, the calibration must include a precise measurement of the FSR of the cavity. Once the exact value of the FSR is obtained, the difference frequency can be determined, in principle, to within an accuracy of $\sim 10^{-10}$, if the temperature fluctuations of the cavity are kept below ~1 degree, because of the extremely low thermal expansion coefficient of the ULE material. Well known molecular lines in the THz region, such as the rotational transitions of carbon monoxide (CO), are suitable for accurate calibration since the frequencies of these THz molecular transitions correspond to 300 times the FSR and can be easily measured to within an accuracy of $\sim 10^{-7}$. Absorption measurements for CO lines with J = 1-10 over the range of 230 GHz to 1267 GHz were carried out by the same configuration as the acetonitrile measurements. From this data set, the average of the FSR value for all CO line measurements was determined to be 2,996,757.48±0.10 kHz. This absolute frequency accuracy of $\sim 10^{-8}$ is at least one order of magnitude better than that obtained in previous work (Nolt et al. 1987).

5. THZ OUTPUT POWER

The photomixer used in the spectroscopy provides currently a maximum output power of approximately 0.1 μW at 1 THz for a pump laser power of 30 mW. However, the power requirement for the LO application is far more demanding. Taking into account the coupling losses into the receiver, a minimum output of 1 μW is required to obtain the minimum noise temperature.

Making the electrode gaps smaller to shorten the carrier transit time should be effective to obtain higher photocurrent and output power, but the smaller the electrode gap, the greater the capacitance will be which limits the device bandwidth. Since the resonant antenna has a frequency dependent complex impedance particularly near the resonance of the antenna itself, the capacitance accompanying the antenna is canceled out by the inductive part of the impedance at a certain frequency. Therefore, the photomixer with the resonant antenna can avoid the output power reduction due to the RC time constant and enjoy its high impedance at the resonance. The dash-dot curve in Figure 2 is the output spectrum from a dipole antenna photomixer. The impedance of the dipole device at the resonance would be about 300Ω according to the power gain from the device with the frequency independent antenna which is shown by the dashed curve in Figure 2.

The major drawback of the resonant antenna device is its narrow spectral bandwidth. Another way to provide a capacitance-free bandwidth is the traveling-wave approach to the photomixer design. One implementation of a traveling-wave photomixer consists of a 0.5-mm long coplanar transmission line with a 2-μm gap formed directly on a LTG-GaAs layer (Matsuura et al. 1998; Matsuura et al. 1999). The device is illuminated from the top by two laser beams with a slight angle between them, which creates traveling optical fringes along the transmission line. The offset angle is tuned to match the velocity of the optical fringes to the velocity of the THz signal in the transmission line. Since the transmission line has the distributed real impedance, the bandwidth of this type of device is not limited by the local capacitance. The solid curve in Figure 2 is the result from the traveling-wave photomixer. The output spectrum of this device is very flat, and the roll-off at higher frequencies is gentle as is expected from the capacitance-free bandwidth. The results from this device are promising and have achieved record power levels above 2 THz (Matsuura et al. 1999).

The most straightforward approach to obtain a higher output power is supplying a higher laser power and bias field to the photomixer. In the high bias field regime the THz output shows a saturated power dependence on the bias due to the field dependent carrier lifetime (Zamdmer 1999). On the other hand, pumping the device with a higher laser power simply increases the output THz power, and the saturation effect, such as the carrier screening, has never been observed. However, the maximum pump laser power is currently limited to approximately 50 mW by thermal failure of the photomixer (Verghese, McIntosh, & Brown 1997), and the output power measured in previous work has therefore been limited to sub-μW levels. To overcome the thermal failure limit, photomixers with higher thermal conductivity substrates are being developed (Verghese, McIntosh, & Brown 1997; Jackson 1999). The traveling-wave photomixer described above has an active area of about 1000μm^2, and it should also alleviate the thermal failure problem with the small area devices. Such photomixers can be driven at the full output of the high-power laser system reported here, and would ultimately produce power levels of nearly 10 μW.

6. SUMMARY

We presented a highly tunable, compact solid-state THz source based on the photomixing with the LTG-GaAs photoconductor. The type of THz source demonstrated here should be useful as LOs for future space-borne and ground-based THz heterodyne receivers to be used in astronomy. The advantage of space-bone telescopes in the THz range is their continuous, wide frequency coverage, which is prevented by strong atmospheric water line absorption at low altitudes. The wide tunability of the photomixer LOs will make it possible to construct highly tunable heterodyne receivers with a single local oscillator and a single mixer. Properties of the present laser system such as its small size, low power consumption, and fiber-connectorized optics also make it highly suitable for space-borne instruments. The development of such remote sensing THz spectrometers is currently in progress. Ground based instruments will benefit from the ability of the photomixer LOs to be controlled optically. In an interferometer array, all the LOs could be controlled via fiber optical link from a central location. A joint European/US/Japan project, the Atacama Large Millimeter Array, is planned to have over 50 telescopes in an array with separations of up to 10 km between telescopes. Each telescope will have 10 heterodyne receivers covering the range from 30-900 GHz. The current plan calls for development of a photomixer based LO.

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