Integrated terahertz source based on three-wave mixing of whispering-gallery modes

Alessio Andronico,1 Julien Claudon,2 Jean-Michel Gérard,2 Vincent Berger,1 and Giuseppe Leo1,*

1Laboratoire Matériaux et Phénomènes Quantiques, CNRS-UMR 7162, Université Paris Diderot-Paris 7, Case Courrier 7021, 75205, Paris Cedex 13, France
2CEA-CNRS Group Nanophysique et Semiconducteurs, CEA/INAC/SP2M, 17 Avenue des Martyrs, 38054 Grenoble, France

*Corresponding author: giuseppe.leo@univ-paris-diderot.fr

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We propose an integrated terahertz emitter operating at room temperature between 2.4 and 6 THz. Based on difference-frequency generation in a triply resonant Au/AlAs/GaAs/AlAs/Au microcylinder, this nonlinear source is pumped by two near-IR whispering-gallery modes that are excited by InAs quantum dots embedded in the resonator. In the vertical direction, these pump modes are due to total internal reflection at GaAs/AlAs interfaces, while the terahertz mode is confined between the metallic layers. This parametric source offers potential advantages with respect to existing terahertz sources for spectroscopic applications, such as room-temperature operation and electrical pumping. © 2008 Optical Society of America

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The field of terahertz applications can be broadly split into broadband time-domain spectroscopy (TDS) and single-frequency (cw) spectroscopy. In TDS, the terahertz source is often a photoconductive dipole antenna excited by femtosecond lasers. This technique has also proven to be a powerful tool for imaging [1]. However, besides requiring costly and often voluminous mode-locked lasers, it allows a limited frequency resolution ($\Delta f \sim 5 \text{ GHz}$). On the other hand, narrowband terahertz systems have found many applications in atmospheric and astronomical spectroscopy, where a high spectral resolution (1–100 MHz) is generally required [2].

Among the existing cw terahertz sources, it is worth mentioning at least two. The first one, also known as photomixing, makes use of semi-insulating or low-temperature-grown GaAs [3]. This technique has been recently extended to the InGaAs material system, allowing the use of pump lasers operating at 1.06 $\mu$m [4]. However, to our knowledge no breakthrough in terms of output power has been demonstrated in cw photoconductive generation during the past few years, and output powers are in the 100 nW range.

The second one is the quantum cascade laser (QCL), where photons are emitted by intersubband optical transitions between coupled quantum wells [5]. QCLs have been recently demonstrated in the terahertz region [6], where they are poorly tunable and only operate at cryogenic temperatures.

Besides these schemes, an interesting approach for the generation and amplification of new frequencies, both pulsed and cw regime, is based on second-order nonlinear processes; in [7] Vodopyanov et al. demonstrated the generation of 0.9–3 THz radiation in periodically inverted GaAs, with optical to terahertz conversion efficiencies of $10^{-3}$, using a pulsed parametric amplifier system centered at $\sim 3 \mu$m. With respect to terahertz generation in LiNbO$_3$ [8], GaAs constitutes an interesting choice, thanks to its large nonlinearity and inherently low losses at terahertz frequencies ($\sim 1 \text{ cm}^{-1}$). To avoid the technological complexity of periodically inverted GaAs sources, it has been proposed to exploit the anomalous dispersion created by the phonon absorption band in GaAs to phase-match a difference-frequency generation (DFG) in the terahertz range [9].

In this Letter we investigate a cw room-temperature terahertz source based on DFG from two near-IR whispering-gallery modes (WGMs) in a high-quality-factor GaAs microcylinder (MC). These modes experience a quasi-phase matching (QPM) owing to an effective $\chi^{(2)}$ modulation along their path [10,11], granting efficient terahertz generation.

The microcavity, as sketched in Fig. 1, is a cylinder composed of a central GaAs layer sandwiched between two lower-index AlAs layers capped on both sides by a metallic film (e.g., Au). This configuration provides both vertical dielectric confinement for the near-IR pump modes and plasmonic confinement for the terahertz mode as illustrated in Fig. 2. The design stems from two opposite requirements on the thickness of AlAs layers aimed at increasing the DFG efficiency: maximize the overlap between the interacting modes and prevent the exponential tails of the near-IR modes from reaching the metallic layers.

In the horizontal plane, the light is guided by the bent dielectric/air interface, which gives rise to high-$Q$ WGMs as observed in [12,13]. The central GaAs layer

![Fig. 1. (Color online) Sketch of a Au/AlAs/GaAs/AlAs/Au MC. The central GaAs slab allows one to vertically confine the two near-IR modes, whereas the metallic mirrors provide plasmonic vertical confinement for the terahertz WGM.](image-url)
contains one or more layers of self-assembled InAs quantum dots (2Ds), which excite the two near-IR modes and can be pumped either optically or electrically. The simultaneous lasing of these modes, without mode competition, can be obtained thanks to the inhomogeneously broadened gain curve of the QD ensemble as observed for QDs in microdisks at temperatures as high as 300 K [14,15] and in MCs [12].

The WGM spectrum of the cavity is easily found with the effective index method (EIM), which reduces the Helmholtz equation in cylindrical coordinates from three-dimensional (3D) to two-dimensional (2D) [12]. As detailed in [16], the latter can be solved in terms of Bessel ($J_m$) and Hankel ($H_m^{(2)}$) functions. The solution $\psi_\alpha$ in the $y$–$z$ plane is

$$\psi_\alpha = \begin{cases} J_m(kn_a)p)e^{-jm\theta} & \rho \leq R \\ BH_m^{(2)}(kp)e^{-jm\theta} & \rho > R \end{cases},$$

where $\alpha = \text{TE/TM}$, $\psi_{\text{TE}} = H_y$, and $\psi_{\text{TM}} = E_x$; $\tilde{\omega}$ is the complex angular frequency $\tilde{\omega} = k + \omega$ with $k$ as the wavenumber; and $B = j n_m R / H_m^{(2)}(kR)$. Once the eigenvalue $\tilde{\omega}$ is known, the radiation limited quality factor can be calculated as $Q' = \text{Re}(\tilde{\omega})/[2 \text{Im}(\tilde{\omega})]$. This expression is expected to properly estimate the quality factor of the terahertz WGM, whose wavelength is of the order of the device size. Conversely, it gives huge values for the near-IR WGMs; their radiative losses are in fact extremely small, and their $Q$ factors are limited by extrinsic losses, such as scattering by sidewall roughness [12,15].

The nonlinear mixing can be studied with the coupled mode theory [17]. In particular, the equation for the terahertz mode amplitude $a_3$ can be written as

$$\frac{da_3}{dt} = j\omega_3 a_3 - \left( \frac{1}{\tau_3} + \frac{1}{\tau_3^{\text{rad}}} \right) a_3 + s^{\text{NL}},$$

where $\omega_3 = \text{Re}(\tilde{\omega}_3)$, $\tau = \tau^{\text{rad}}$ accounts for radiation (material) losses and $\tau^{\text{rad}} = 2Q_3^{\text{rad}} / \omega_3$. The $s^{\text{NL}}$ term represents the nonlinear polarization source and is given by

$$s^{\text{NL}} = -j \frac{\omega_3}{4} a_1 a_2^{*} I,$$

where $I$ is the nonlinear overlap integral

$$I = \int_V \sum_{ijk} e_0 \chi^{(2)}_{ijk} E_i^{*}(\omega_3) E_j(\omega_1) E_k^{*}(\omega_2) dV,$$

with $V$ the cavity volume and $\chi^{(2)}$ the nonlinear tensor. For a [100]-grown GaAs the nonlinear source differs from zero when (1) two of the three WGMs are TE polarized and one is TM polarized and (2) the phase-matching condition $\Delta m = m_2 + m_3 - m_1 \pm 2 = 0$ is satisfied. If $A_3$ is the steady state solution of Eq. (2), the radiated terahertz power is

$$P_3^{\text{rad}} = \frac{2|A_3|^2}{\tau_3} = \frac{\omega_3}{4} \frac{Q_3^2}{(1 + Q_3^2/Q_3^{\text{rad}})^2} U_1 U_2 |I|^2,$$

with $U_1$ and $U_2$ as the electromagnetic energy stored in the two pump WGMs. By numerically studying the structure of Fig. 1 with $w = 0.325 \mu m$ and $h = 6 \mu m$, we find that a radius $R = 40.6 \mu m$ allows one to phase match two pumps near $1 \mu m$ ($\lambda_1 = 0.923$ and $\lambda_2 = 0.936 \mu m$) and a terahertz WGM with $\lambda_3 = 63.4 \mu m$ (i.e., $\nu_3 = 4.8$ THz). The corresponding azimuthal numbers are $m_1 = 917$, $m_2 = 913$, and $m_3 = 2$, and the calculated terahertz WGM quality factors are $Q_3^2 = 39$ and $Q_3 = 113$.

It is important to observe that, since the WGMs excited by the QDs are TE polarized, the terahertz WGM is a TM mode. Under the hypothesis of an overall quality factor $Q = 10^5$ for the two pump modes [15], we can make important statements for our source: (1) its estimated phase-matching width, dictated by the finesse of the near-IR WGMs, is $3 \text{ GHz}$, and (2) under the conservative assumption of extracting $1 \text{ mW}$ (corresponding to a circulating power of $16 \text{ mW}$) from each of the pump modes, the emitted terahertz power is expected to be $P_3^{\text{rad}} \sim 1 \mu W$. At these pump powers, two-photon absorption does not affect the performance of our device and can be safely neglected in the calculations.

Figure 3 shows the far-field pattern of the source at room temperature as obtained following the semi-analytic method developed in [16]. The emission is concentrated at high angles owing to the strong diffraction experienced by the tightly confined terahertz mode.

In Fig. 4 we report the effect of radius fabrication tolerance on the generated terahertz frequency for three different temperatures. Please note that the slight terahertz frequency shift resulting from non-nominal fabrication is comparable to the phase-matching spectral width and is therefore negligible. It is worth stressing that once the temperature has been chosen, each point in Fig. 4 corresponds to a phase-matched triplet with fixed azimuthal numbers on each curve.
Finally, we remark that two independent factors determine the terahertz wavelength range covered by our device. At 300 K, the homogeneous broadening of QDs is of the order of 10 meV [18], which restricts the terahertz generation to frequencies $\nu_3 > 2.4$ THz. Emission at lower frequencies can be obtained by reducing the QDs homogeneous broadening, although at the expense of a low-temperature operation. Conversely, the upper limit is set by the GaAs Rest–Strahlen band, i.e., $\nu_3 < 6$ THz.

In conclusion, we have designed a cw terahertz source based on intracavity three-wave mixing between WGMs. As compared to existing terahertz sources, it combines room-temperature operation, relatively high output power, narrowband emission, compactness, and fabrication simplicity. It also promises interesting perspectives in terms of electrical injection, multispectral emission with 2D MC arrays, and coherent detection schemes.

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References