Photonic THz generation in GaAs via resonantly enhanced intracavity multispectral mixing

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We generate tunable (1.5–2 THz) terahertz output with up to 200 μW average power in periodically inverted GaAs using resonantly enhanced multispectral frequency mixing inside the cavity of a type-0 optical parametric oscillator operating at degeneracy. The optical parametric oscillator was synchronously pumped by a 1064-nm picosecond Yb-fiber laser and produced, due to the presence of an intracavity Fabry-Pérot etalon, a set of optical frequency peaks spaced at the desired THz interval that allows efficient THz wave production via difference frequency generation. The proposed method is well adapted for cascaded THz generation, where the quantum conversion limit can be significantly surpassed. © *2011 American Institute of Physics*. [doi:10.1063/1.3617435]

Terahertz generation via frequency down conversion in electrooptic crystals is an attractive way of producing frequency-tunable THz waves, thanks to the progress in developing quasi-phase-matched (QPM) structures like GaP and GaAs, as well as compact and efficient optical pump sources including fiber lasers. Nevertheless, because of the Ω^3 scaling factor[1] (Ω is the THz angular frequency), optical-to-THz conversion efficiency is intrinsically low, as compared to the similar case of mid-IR generation, and thus much higher pump power is required to approach the quantum conversion limit.

One of the means to circumvent this problem is an enhancement of the optical field inside a resonant cavity. For example, THz outputs with mW-level average power were produced via difference frequency generation (DFG) in a QPM GaAs placed inside the cavity of a doubly resonant synchronously pumped type-II picosecond optical parametric oscillator (OPO),[2] via DFG in periodically poled lithium niobate (PPLN) crystal placed inside the cavity of a dual-color continuous-wave (CW) vertical external cavity surface emitting laser (VECSEL),[3] and via DFG in a bonded QPM GaP crystal where the two interacting pump fields of a nanosecond (ns) C-band ($\sim$1500 nm) fiber laser were enhanced in an external ring-type cavity.[4] Also, μW-level THz outputs were demonstrated in a CW (Ref. 5) and a *ns* (Ref. 6) THz OPOs based on PPLN with resonantly enhanced pump, and in *ns* THz OPOs based on bulk (Ref. 7) and periodically poled lithium niobate,[8] where the OPO and the pump 1064-nm laser shared the same cavity.

Here we propose a method for efficient THz-wave generation based on DFG within a *sequence* of equally spaced frequency peaks enhanced by a resonant cavity.

Frequency peaks in the 2-μm band were produced inside a ring-cavity OPO (Fig. 1) operating near degeneracy. The OPO was synchronously pumped by an Yb-doped fiber laser (Fianium FP1060-10) with the central wavelength 1064 nm, pulse repetition rate 109 MHz, pulse duration 10 ps, and average power up to 6.7 W. The OPO cavity had a 275-cm roundtrip length to match the laser repetition rate and was composed of two pairs of concave mirrors with radii of curvature R = 200 and 500 mm and a pair of flat folding mirrors. All mirrors were nearly transparent at the pump wavelength and had high (>99.9%) reflectance near 2 μm. The OPO gain medium was an antireflection (AR) coated 10-mm-long, 1-mm-thick MgO: PPLN crystal from HC Photonics, kept at 151 °C, with a QPM period of 31.8 μm designed for type-0 phase-matched ($e = e + e$) degenerate operation near $\lambda = 2.1$ μm. For intracavity THz DFG, we used optically contacted stacks of GaAs (OC-GaAs) produced in-house. The samples were approximately 6 and 8 mm long (stacks of 11 and 15 wafers), with the inversion period around 1060 μm. With antireflection coatings applied, total transmission losses of our OC-GaAs samples did not exceed 3% near $\lambda = 2.1$ μm. The computed beam waists (1/e^2 intensity radii) of the resonating OPO eigenmode were w = 70 μm (at PPLN) and w = 250 μm (at GaAs).

A thin (d = 50–60 μm) Fabri-Perot etalon made of undoped YAG was placed inside the OPO cavity to modulate the spectrum and create a set of peaks spaced by the etalon's free spectral range (FSR), equal to a desired THz frequency.

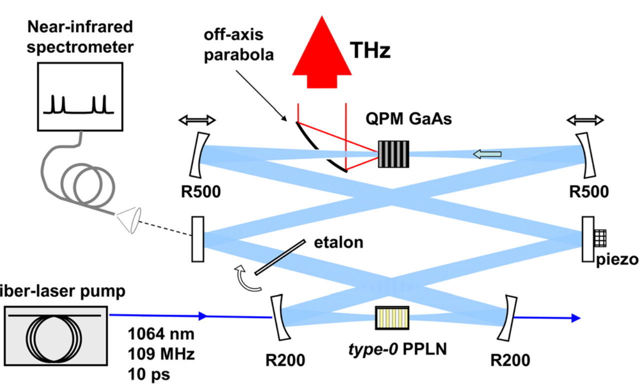

FIG. 1. (Color online) High-finesse degenerate ring-type OPO, synchronously pumped by a picosecond fiber laser, for THz generation via intracavity multispectral difference frequency mixing in GaAs.

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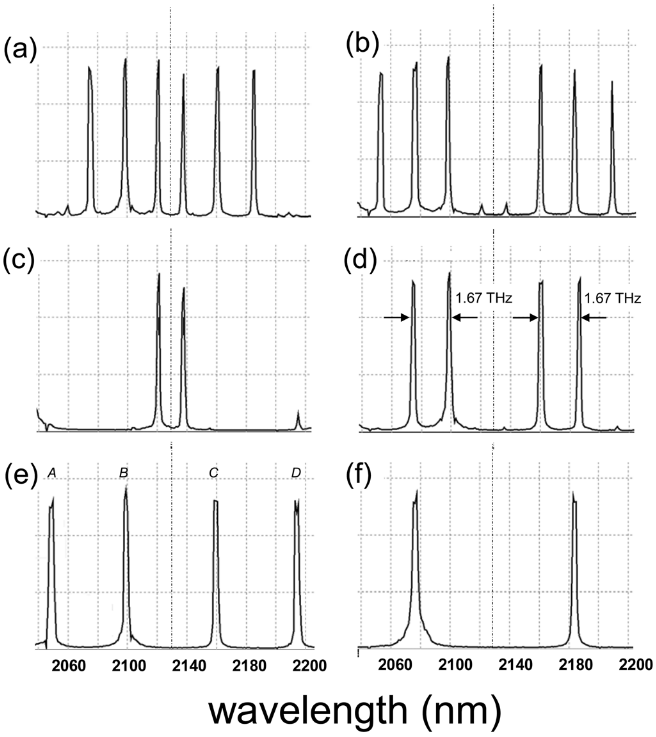

FIG. 2. Real-time OPO spectra recorded with a near-IR spectrometer at different OPO cavity lengths and a d = 57 μm YAG etalon with a fixed tilt angle (25°) and a nominal FSR of 1.5 THz. Vertical dashed-dotted line corresponds to the OPO degeneracy point. One horizontal division (20 nm) corresponds to 1.325 THz.

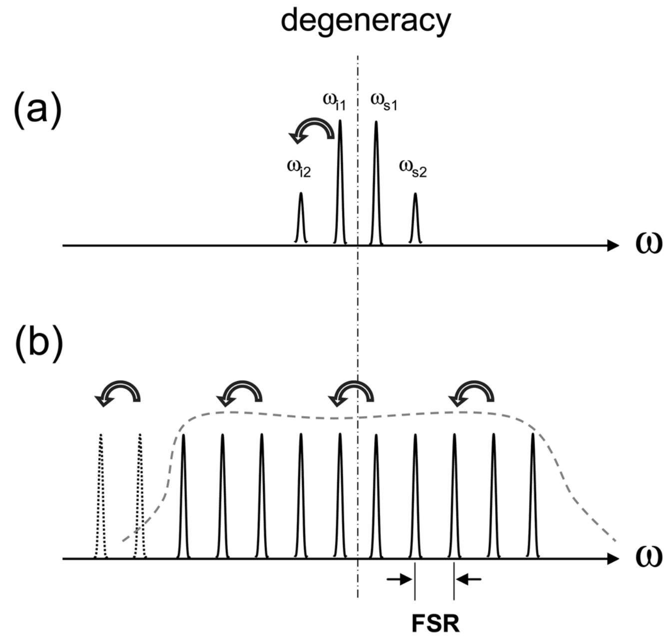

FIG. 3. Conceptual picture of (a) establishing coherence between neighboring optical peaks and (b) cascaded THz generation. Dashed line represents OPO gain bandwidth.

Due to the doubly resonant condition, the OPO pump threshold was very low, corresponding to 20 mW of average pump power without GaAs in the cavity, and to 40–80 mW with GaAs present. The roundtrip loss in the "empty" cavity was estimated to be 2%–3%. At 6.7 W of average pump power, the 2.1-μm intracavity average power (measured by monitoring power leakage through one of the highly reflecting mirrors) exceeded 100 W.

The OPO spectrum was monitored in real time with a fiber-coupled NIR QUEST-256-25 spectrometer from Ocean Optics. By slow ramping the cavity length with a piezo actuator, at approximately 1 μm per minute, we were able to obtain a variety of spectral outputs (Fig. 2). These variations of the spectrum result from the condition that at each cavity length the signal and idler modes should resonate simultaneously, which is satisfied (in the presence of dispersion) for only a certain group of modes, the effect known as "mode clustering."[9] The common features of the spectra of Fig. 2 are as follows: (1) peaks are always mirror-symmetric with respect to the degeneracy (2128 nm) and (2) peaks are spaced by approximately an integer number of etalon FSRs, the latter being determined by the etalon thickness and tilt angle. For example, in Fig. 2(a), the spacing between all peaks is roughly equal to FSR, while in Fig. 2(e), the spacing between the peaks A-B and C-D is 2 × FSR, and between B-C is 3 × FSR. In general, we were able to observe up to 10 spectral peaks produced at a time. Also, we were able, by slightly changing the tilt of the etalon, to switch between the two frequency states: "even" and "odd." In the "even" state, the 2128-nm degeneracy point is exactly in the middle between the two neighboring peaks (as in Fig. 2), while in the "odd" state (not shown), one of the peaks coincides with the degeneracy. We should note that one can stabilize the OPO cavity length to produce a constant spectral output, via a servo loop[2] using a piezo actuator attached to one of the mirrors and an infrared detector for the feedback.

The THz output was collected by a 2-inch (50-mm) 90° off-axis parabolic mirror with a 3-mm hole to transmit the resonating optical beam and detected using a Golay cell (Fig. 1). Black polyethylene filters were used to block the 2-μm radiation. With the $L = 6$ mm OC-GaAs, we measured 200 μW of average power at around 1.6–1.7 THz. The intracavity circulating average optical power at 2 μm was estimated to be 20–30 W.

Simple calculations show that if there are N equidistant frequency peaks inside the cavity and the total intracavity power P_0 is fixed, then, if all THz fields produced by neighboring optical peaks add coherently, the generated THz power scales as

$$P_{THz} \sim P_0^2 \left[\frac{N-1}{N}\right]^2 \qquad (1)$$

and increases with N. In fact, optical power per peak is $P_n \sim P_0/N$; electric field in each peak $E_n \sim \sqrt{(P_0/N)}$; THz field generated by one pair of peaks is $E_n^T \sim E_n E_{n+1} \sim (P_0/N)$; coherent sum of N-1 THz fields is $E^T \sim (P_0/N)(N-1)$; thus, total THz power $\sim P_0^2[(N-1)/N]^2$. For example, 10 peaks will produce 3.2 times more THz power than one pair ($N = 2$).

One possible scenario for establishing coherence between neighboring optical peaks (and thus between THz fields) is as follows. Imagine that we start with one signal-idler pair ω_{s1} and ω_{i1} spaced by ω_{THz} (Fig. 3(a)). As a general property of 3-wave interactions, there is fixed relationship[10] between the phases of the signal, idler, and the pump (ϕ_p),

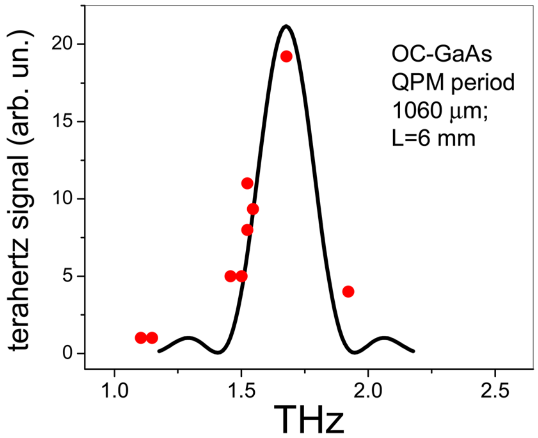

FIG. 4. (Color online) THz output from the OC-GaAs as a function of frequency spacing between the Fabri-Perot peaks. Solid line represents theoretical phase-matching curve.

$$\phi_p = \phi_{s1} + \phi_{i1} + \pi/2. \tag{2}$$

Similarly, the phase of the THz wave (ϕ_{THz}) generated via DFG is related to the phases of the waves which produce it,

$$\phi_{s1} - \phi_{i1} = \phi_{THz} + \pi/2. \tag{3}$$

Now, if the THz wave interacts with the idler wave ω_{i1} to produce red-shifted peak ω_{i2}, then

$$\phi_{i1} - \phi_{i2} = \phi_{THz} + \pi/2. \tag{4}$$

Via interacting with the pump, the wave ω_{i2} will produce another wave $\omega_{s2} = \omega_p - \omega_{i2}$, with their phases related as

$$\phi_p = \phi_{s2} + \phi_{i2} + \pi/2. \tag{5}$$

By subtracting Eqs. (2) from (5), we obtain

$$\phi_{s2} - \phi_{s1} = \phi_{i1} - \phi_{i2}. \tag{6}$$

From Eqs. (3) and (4) and (6), it follows that all three pairs of optical waves are in phase with each other.

In our experiment, the maximum THz output was generated in cases (c) and (d) of Fig. 2, and less THz power was produced in the case (a). This can be accounted for by the fact that the peaks in Fig. 2(a) were *not equidistant*. In general, spacing between the peaks experienced as much as ±25% variation from the nominal grid set by the etalon and is larger than the THz acceptance bandwidth of GaAs: for a QPM GaAs with $L = 6$ mm, the measured acceptance at half maximum was ±9% of central THz frequency (Fig. 4) and was close to theory. The non-uniformity of peak spacing is the result of (1) cavity group delay dispersion (GDD) and (2) low finesse of our uncoated YAG etalon which produces only ∼30% spectral modulation. The THz output can be significantly improved by making the peaks equally spaced which can be achieved through: (1) reducing GDD in the cavity (e.g., by reducing PPLN length and/or adding a dielectric plate with the opposite-sign GDD) and (2) by using a higher finesse etalon. Also, the pulses of our pump fiber laser were chirped (time-bandwidth product was 3 times larger than the Fourier limit), which, we believe, negatively affected coherence properties of the OPO.

Potentially, our method allows continuous tunability through the whole spectral range of 0.5–4 THz (limited by the Ω^3 factor on the lower side and GaAs absorption on the higher side) and can be achieved by using an air-gap etalon with a variable spacing and by using a "fanned-out" GaAs crystals where the QPM period varies across the beam (allowed by epitaxial growth technique of "orientation-patterned" GaAs (Ref. 11)). Also, multiple THz frequencies can be attained with a single periodically inverted GaAs sample using higher-order (3rd and 5th) QPM.[1]

Our method of intracavity multispectral mixing can be used in a variety of configurations including laser media with broadband gain (e.g., semiconductor and solid state) and in different time formats (CW, *ns*, and *ps*). Finally, this method, quite naturally, sets the stage for *cascaded* THz generation: as the optical pump frequencies run down the Stokes ladder, the number of terahertz photons should continually increase[12] (Fig. 3(b)). In such a *cascading* system, one can exceed the Manley-Rowe quantum conversion limit by as much as a factor of ten in GaAs.[13] In practice, the occurrence of red-shifted features due to THz cascading has already been demonstrated in a number of experiments for narrowband[2,6,8,14] and broadband[15,16] photonic THz generation.

In conclusion, we present a technique for resonantly enhanced THz generation using frequency mixing between adjacent equally spaced frequency peaks of a broadband optical source. This method represents a path to creating a broadly tunable highly efficient room temperature photonic THz source, which can potentially reach and even surpass the quantum limit of optical-to-THz energy conversion.

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