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Citation: Appl. Phys. Lett. **92**, 141105 (2008); doi: 10.1063/1.2907489
View online: http://dx.doi.org/10.1063/1.2907489
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v92/i14
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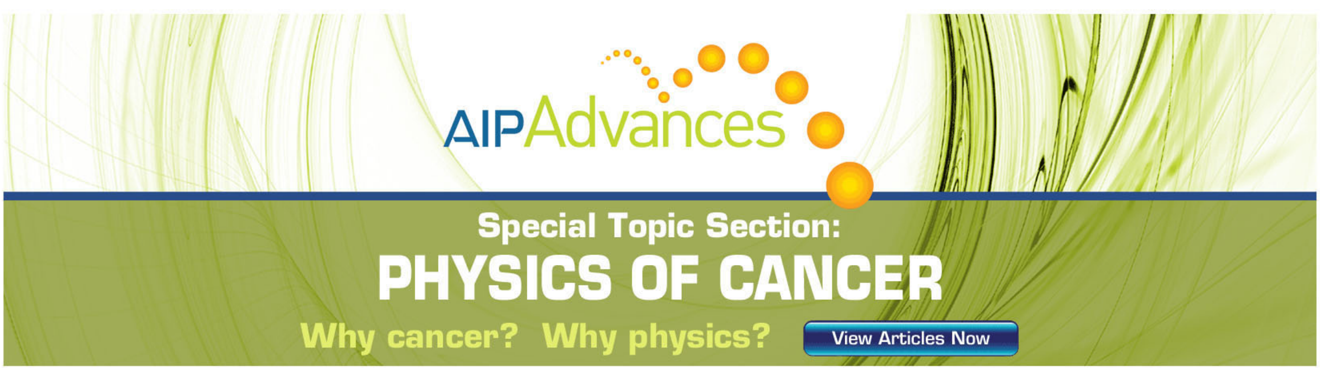

Line-narrowed, compact, and coherent source of widely tunable terahertz radiation

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(Received 22 January 2008; accepted 18 March 2008; published online 8 April 2008)

We report a technique for line-narrowing terahertz radiation produced through parametric generation. By incorporating an etalon within the idler-wave cavity of the parametric oscillator, radiation is generated with a linewidth of 1 GHz (freerunning linewidth 50–100 GHz) and with a center frequency continuously tunable over a band >50 GHz, settable anywhere within the coarse tuning range of the device (1–3 THz). When implemented within an intracavity cavity geometry, pulses of terahertz radiation of duration ~10 ns and energy ~30 nJ are generated at repetition rates up to 400 Hz (implying mean powers of >10 μW and peak powers of ~3 W) in a compact device. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2907489]

The generation of tunable terahertz radiation is currently of widespread interest with potential applications identified in many areas of science and technology. Sources based on parametric oscillation/generation continue to make a significant contribution, in particular, since they may be widely and continuously tuned, thereby addressing important applications in spectroscopy and hyperspectral imaging.[1–6] The noncollinear phase-matching geometry generally employed allows wide tuning (typically 1–3 THz) to be obtained through changing the angle between the resonated idler wave and the pump wave, when the accompanying linewidth is typically 50–100 GHz.[1] Linewidth reduction in such sources is therefore a particular concern.

In the present communication, we report a scheme for routinely reducing linewidths by a factor of 10–20 to <5 GHz and, with further refinement, ultimately to <1 GHz, in both cases without significant loss in the terahertz energy/power. Linewidth reduction is effected by the insertion of suitable etalons within the idler-wave and pump-wave cavities of the parametric oscillator. Further, the generated terahertz radiation may then be continuously fine tuned over a band >50 GHz simply by scanning one parameter of the system, namely, the angular orientation of the etalon in the idler-wave cavity and where this band may be set anywhere in the coarse tuning range (1–3 THz).

The device, schematically shown in Fig. 1, is based on a compact, Q-switched, diode-laser-pumped Nd:YAG (yttrium aluminum garnet) laser providing the pump-wave for the parametric oscillator. It incorporates two intersecting cavities in which the nonlinear (NL) medium providing the parametric gain (magnesium oxide doped lithium niobate) is located both within the cavity of the pump laser (intracavity geometry), defined by mirrors M1 and M2 and, simultaneously within the idler-wave cavity, defined by mirrors M5 and M3. This arrangement leads to an order of magnitude reduction in the pump power required to reach oscillation threshold, accompanied by greater than an order of magnitude increase in the energies of the terahertz pulses generated compared to conventional extracavity devices.[6] The Nd:YAG laser gain crystal is end-pumped by a fiber-coupled quasi-cw diode laser with aspheric lenses used to optimize the dimensions of the pumped volume. The Nd:YAG laser is Q switched by an electro-optic Q switch used in combination with a linear polarizer and a quarterwave plate, resulting in the generation of pump-wave pulses of typical duration 10–20 ns, with associated idler-wave pulses of typical duration 10 ns at repetition rates of up to 400 Hz. A silicon prism array attached to one side of the nonlinear medium couples the terahertz output into freespace (large arrow).[4]

In the present device, coarse tuning is effected by appropriate adjustment of mirrors M5 and M3 so as to set the angle between the idler-wave and the pump-wave cavities to the value required by the range of terahertz frequencies to be covered through subsequent fine tuning. This range can be anywhere within the coarse tuning range previously reported (1.2–3.05 THz).

The linewidth of the device is reduced by the use of (i) a solid etalon E2 (thickness=600 μm, free spectral range (FSR)=170 GHz and finesse≈14) located within the idler-wave cavity and (ii) a solid etalon E1 (thickness=600 μm, free spectral range (FSR)=170 GHz and finesse≈3) located within the pump-wave cavity. Constraining the frequencies of both pump- and idler-waves by means of these etalons results (through energy conservation during the parametric process) in an associated constraint on the linewidth of the terahertz radiation generated. Fine tuning is effected by rota-

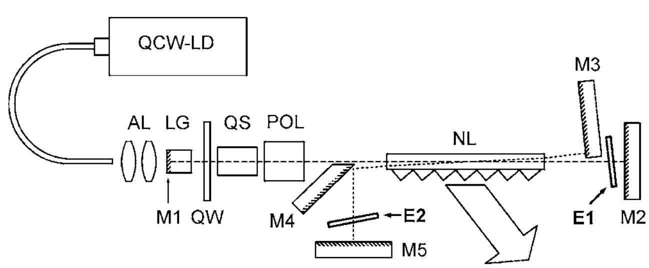

FIG. 1. Layout of the terahertz parametric generator.

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tion of etalon E2, which is mounted on a servocontrolled galvanometer

An Angstrom WS7-L MC Wavelength Meter[7] was used to measure the pump-wave and idler-wave frequencies and linewidths. A number of etalon combinations were explored with regard to both their free spectral range and their finesse, the former being chosen so as to exceed the gain bandwidth over which selection was being effected, the latter being chosen as a compromise between attained minimum linewidth and walk-off loss. The etalon combination as detailed above was found to be the most effective in these regards given the range of etalons available to us. The freerunning multiaxial-mode Nd:YAG laser linewidth, with etalon E1 removed from the cavity was found to be ≈25 GHz. Insertion of etalon E1 constrained this to <1 GHz. Insertion of etalon E2 into the idler cavity provided two advantages. The first was to reduce the idler-wave linewidth for a single pulse to <1 GHz (from 50 to 100 GHz freerunning). The second was to enable fine-frequency tuning of the idler wavelength through tilting the etalon. In this way it was possible to smoothly and continuously tune the idler-wave frequency and hence the associated terahertz-wave frequency over the full phase-match bandwidth (typically 60–70 GHz) as defined by the angle between the optical axes of the pump-wave and idler-wave cavities.

From the above measured single-pulse linewidths of the pump wave and the idler-wave, the linewidth of the terahertz radiation was deduced to be <1 GHz for a single pulse. We also directly measured the linewidth of the terahertz radiation using a Fabry-Perot interferometer. When averaging (typically) over some 30 pulses in this case the linewidth was found to be ≤5 GHz. This increase in linewidth was due to the pulse-to-pulse instability of the frequency of the idler pulse; this being confirmed by direct measurement with the wavemeter.

The significant reduction in pump power/energy requirements afforded by the intersecting cavity geometry compared to earlier reported extracavity geometries, as previously reported by us,[6] was maintained following implementation of the linewidth reduction scheme. For example, insertion of the etalon in the idler-wave cavity resulted in the pump energy (at a wavelength of 1064 nm) required to reach the oscillation threshold of the parametric oscillator having to be increased by no more than 17%. [Such an increase is consistent with an anticipated walk-off loss of <10% for the etalon when it is tilted through an (internal) angle of around 1° from the normal so as to tune across its free spectral range.] When operating at 1.2× oscillation threshold and with the etalon in place, the parametric down-conversion efficiency was ~32%, compared with ~42% in the absence of the etalon when the device was then operating at 1.4× oscillation threshold. Typically line-narrowed terahertz pulses of temporal width ~10 ns [full width at half maximum (FWHM)] and of energy 30 nJ (peak power ~3 W) were readily generated at repetition rates up to 400 Hz (implying mean powers >10 μW). Such high repetition rates are made possible, while retaining the advantages of a compact device based on diode-laser pumping, through the reduced pump power requirements associated with the intersecting cavity geometry, and allow improved signal-to-noise ratios without the need to extend averaging times.[8] In order to assess the performance of the device we have carried out spectroscopy on

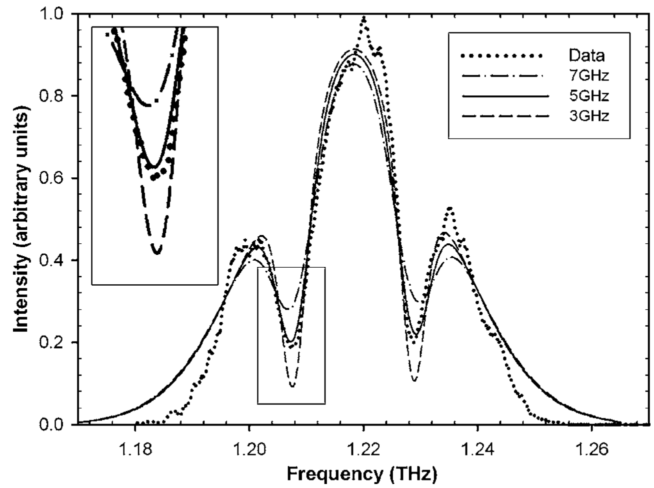

FIG. 2. Absorption spectrum due to two closely spaced water vapor lines at a pressure of 0.18 atm. The dotted line shows the experimental data. The three additional curves illustrate calculated absorption profiles using HITRAN data and assuming FWHM source linewidths of 7, 5, and 3 GHz.

water vapor and, following further refinement, on carbon monoxide.

Figure 2 shows the absorption spectrum due to two closely spaced water vapor lines at 40.283 410 cm^{-1} (1.207 666 THz) and 40.988 310 cm^{-1} (1.228 799 THz).[9] The experimentally measured spectrum, based on averaging over some 30 pulses for each data point, is shown by a bold dotted line for the case where the absorption path length is 27 cm, the water vapor partial pressure is 0.022 atm (saturated water vapor pressure at 18 °C), and the air pressure has been reduced to 0.18 atm. The other curves shown are based on spectral data obtained from HITRAN (Ref. 9) including the effects of pressure broadening, which have been (a) convoluted with assumed linewidth functions for the sources of 7, 5, and 3 GHz (FWHM of Gaussian profile), and (b) multiplied by the measured fine-tuning profile of the source. It may be seen that the best fit of the measured profile to the calculated profiles is for the case where the instrumental linewidth is taken as 5 GHz (FWHM), consistent with our previous findings. Measured profiles subsequently taken at an air pressure of 1 atm clearly showed that the effects of pressure broadening and estimates of the pressure broadening coefficients deduced from these profiles are consistent with data published in HITRAN (i.e., 5.5–5.7 GHz/bar at room temperature).[9]

As discussed previously, the single-pulse linewidth (1 GHz) is significantly smaller than the linewidth when averaged over multiple pulses (5 GHz). This suggested an approach for improving resolution in which the frequency of each individual idler-wave pulse is simultaneously measured (using the wavemeter) and recorded along with the accompanying absorption measurement associated with that pulse. Following the sorting of the acquired data into frequency bins of suitably chosen width (250 MHz), averaging over the data within each bin then yields an absorption spectrum with a resolution matching the single-pulse linewidth. We have adopted this approach in a study of the rotational spectrum of carbon monoxide. As an example, we have measured for the $J=12$ to $J=13$ rotational transition of CO over a pressure range from 0.2 to 1 bar: (i) the effective absorption cross section as a function of pressure

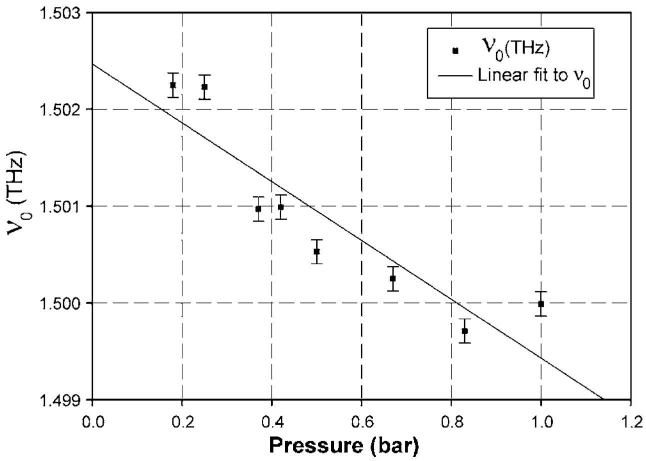

FIG. 3. Self-frequency shift (terahertz) of the $J=12$ to $J=13$ rotational line in the fundamental band of carbon monoxide as a function of carbon monoxide pressure (bar), where ν_0 is the center frequency (terahertz) of the absorption line. Error bars indicate the width of the frequency bins employed.

$$\sigma(p) = \sigma_0 - \sigma_1 p, \tag{1}$$

where $\sigma_0=(5.9\pm0.2)\times10^{-25}$ m^2, $\sigma_1=(2.3\pm0.4)\times10^{-25}$ m^2 bar^{-1}, and p is the pressure in bars; (ii) the (self) broadening coefficient (3.5 ± 0.5 GHz/bar), and (iii) the pressure induced frequency shift (-3.0 ± 0.6 GHz/bar). The results on frequency shifting are illustrated in Fig. 3 below. Early studies by Nazakawa and Tanaka[10] on rotational lines in CO were carried out with a low-resolution spectrometer (0.9 cm^{-1}) at high pressures (>2 bar); the latter resulting in the overlapping of adjacent rotational lines unlike the low pressure case here where an individual, well-separated line is observed. More recently, Matsuura and co-workers[11,12] by using photomixing techniques based on stabilized diode-lasers to generate cw terahertz radiation, have measured the absolute frequencies of rotational lines in CO, contained in low pressure absorption cells, over the range of 0.23 to 1.27 THz and with sub-1-MHz precision, but did not thereby explore pressure broadening or pressure induced frequency shifts.

Terahertz radiation that exhibits multi-pulse-averaged linewidths of less than 5 GHz (FWHM) and that may be smoothly and continuously fine tuned over ranges >50 GHz, settable anywhere in the frequency range from 1 to 3 THz, has been generated by parametric means; frequency control and tuning having been effected by the use of intracavity etalons. Further, by using a wavemeter to monitor individual pulses, spectral resolution has been improved to the subgigahertz level. Significantly, such resolution is particularly appropriate for studies on low pressure gases/vapors in the terahertz spectral range in that it allows pressure-broadening (and pressure shifting) effects, the ultimate determiners of absorption linewidths in these cases, to be measured and studied.

Although injection seeding of parametric generators/oscillators with external tunable lasers has previously been reported to yield source linewidths approaching the transform limit (100 MHz),[13] these sources are more complex in that they involve two separate seeding lasers (one for the pump wave, one for the idler wave) along with optical isolators to eliminate feedback and further optics for mode matching. In addition, they deliver significantly lower pulse energies (~1 nJ) and mean powers (~20 nW) in the terahertz range than the present device.

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) and by the Paul Instrument Fund of the Royal Society of London. Studies on carbon monoxide were carried out in collaboration with the UK National Physical Laboratory.

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