High-power terahertz radiation source based on difference frequency mixing of CO_2 laser lines

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Abstract: A ~2 MW, 250 ps terahertz pulse was generated in a noncollinear phase-matched GaAs crystal at room temperature. Tunable CO_2 lasers in combination with this technique should yield a source in the 0.1-3.0 THz range.

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In recent years there has been significant interest in the development of sources for generation of coherent tunable terahertz (THz) radiation. The most successful techniques for generating narrow-band, high-power THz pulses have come from frequency down-conversion of the existing 1-μm and 10-μm lasers. According to Manley-Rowe relations the maximum power conversion efficiency for the Difference-Frequency Generation (DFG) at $\omega_3=\omega_1-\omega_2$ is limited by the ω_3/ω_1 ratio. Therefore, for applications where kW to MW power levels are necessary at THz frequencies, CO_2-laser-based sources have a natural advantage in the down-conversion process. Recently we proposed to seed an undulator with a THz pulse of MW power produced by DFG in order to modulate an electron beam copropagating with this THz beam at the period of a laser beatwave.[1] Until now the highest power produced by DFG at THz frequencies is ~4kW generated in a GaAs crystal at a liquid-helium temperature.[2] Higher, MW power level has been achieved only in optically pumped molecular lasers on very few fixed frequencies. Here we report the generation of noncollinear phase-matched THz difference frequency radiation by mixing two CO_2 laser lines in a GaAs crystal at room temperature. The measured power at 340 μm (ω_3=0.897 THz) was ~2 MW. By selecting different line pairs a step-tunable radiation in the THz range was obtained.

The experiment has been performed at the Neptune Laboratory at UCLA with a two-wavelength, TW CO_2 master oscillator-power amplifier system.[3] The study of noncollinear mixing of laser lines in a GaAs was divided in two parts. First, we used 200 ns pulses for laser power of 250 kW (intensities of the order of 5-6 MW/cm^2) to optimize phase-matching for THz generation. Having confirmed the technique of noncollinear phase matching, an output beam of the final amplifier with pulse duration of 250 ps (intensities up to 1 GW/cm^2) was sent to the crystal. For the short pulses nonlinear frequency conversion efficiency increases significantly in two ways: first owing to the pump power increase and second, this power can be coupled into a crystal because of the higher damage threshold.

For noncollinear phase-matched mixing of two laser lines of frequencies ω_1 (wavelength 10.3 μm) and ω_2 (10.6 μm) to generate the difference-frequency radiation at ω_3 (340 μm), the conditions of photon energy and momentum conservation require that $\omega_3=\omega_1-\omega_2$ and that matching of the respective wave vectors occurs as shown in Fig. 1. Noncollinear mixing is possible because GaAs possesses anomalous dispersion between the incident CO_2 laser radiation and the THz difference-frequency radiation. Similar to B. Lax et al[1] we found that the phase-matching angle θ for this pair of lines is equal 0.72° and the angle φ at which the THz radiation is generated with respect to the direction of incident radiation is 21.64°. The angle at which THz radiation propagates inside the crystal is greater than the critical angle for total internal reflection. Therefore, as it shown in Fig. 1, the output face of the GaAs crystal (in the form of a 2x4x2.5 cm rectangular parallelepiped) was cut at an angle of ~10° to decouple both 10 μm and 340 μm beams. It is important that the crystal in a noncollinear configuration allowed the separation of the newborn radiation from the pump lasers in space facilitating the use of the THz beam. In the experiment a vertically polarized, two-wavelength CO_2 laser beam was split into two optical arms. Because of the orientation of the crystal, only one wavelength in each arm was utilized for the DFG process. The THz radiation was collected by a cone and sent onto a Golay cell for detection. For a very long base of both arms, we obtained an angle resolution of less than 0.01° while scanning the phase matching angle. Angle tuning showed that the THz signal peaked at θ=0.71° and the half-width of the phase-matching curve corresponded to an effective

length of ~ 1 cm. For 200 ns pulses with a peak power $P_{10.3} \approx P_{10.6} \approx 125$ kW in a focused laser beam we detected THz pulses with a peak power around 0.6 W. At higher peak input power the THz power increased above 1 W, however surface damage occurred after many shots. A narrow–band interference filter centered at 350 μm was used to verify the generated frequency. By selecting the other pair of CO_2 laser lines we obtained 240 μm (1.25 THz) radiation with approximately the same conversion efficiency.

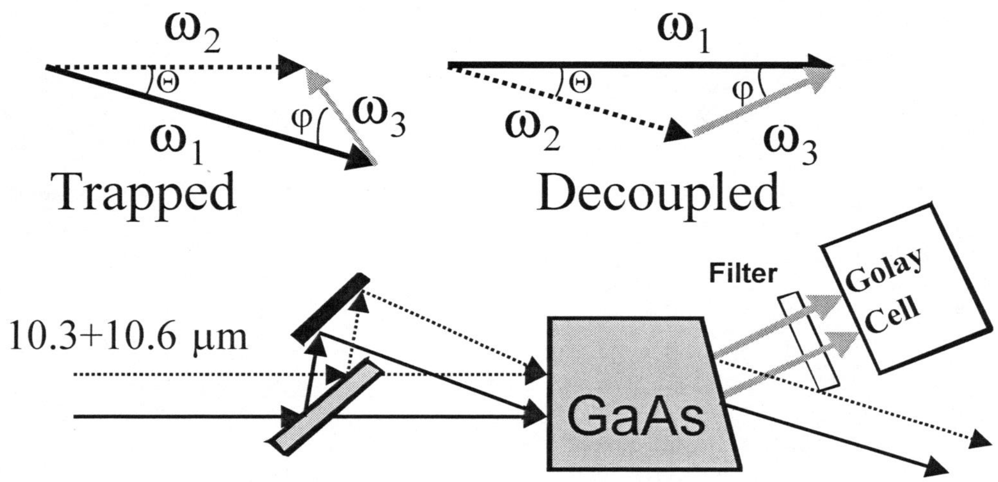

Fig. 1. Schematic wave vector diagram for noncollinear DFG inside the GaAs crystal (a) and optical scheme of an experimental set-up for THz DFG.

It is known that switching to shorter pulses should increase the surface damage threshold of the material and therefore may result in reaching higher conversion efficiency. In a series of damage threshold measurements for 250 ps CO_2 laser pulses, we observed a single shot damage of GaAs at ~0.5 J/cm^2 (≤ 2 GW/cm^2). However, in the experiment for the unfocused 10-μm beam with a cross-section of 3x2 cm, existence of the hot spots seriously limited the incident fluence especially for the multishot exposure. As a result the typical pump intensity did not exceed 1 GW/cm^2. Moreover, using a two-wavelength beam in each arm with a 10/1 –20/1 ratio between the 10.6 and 10.3 μm lines caused the useful pump power to be around 250 MW/cm^2. As shown in Fig.1 a phase-matched THz beam produced by another part of the pump was trapped inside the crystal. The detector placed after a 0.5-m long Cu waveguide measured approximately 250 μJ energy; taking into account the attenuation of the THz transport system up to 0.5 mJ energy was generated in the 2.5 cm long crystal. Using this length and the pump power value of 250 MW/cm^2 over the whole 6 cm^2 beam, we calculate a total power of 2.8 MW for perfect phase-matching and the absorption coefficient at 340 μm equal to 0.2 cm^{-1}. This is in a good agreement with the experimentally measured power of approximately 2 MW assuming a 250 ps long THz pulse. This peak power corresponds to the ~10^{-3} external conversion efficiency. The inhomogeneity of the pump optical beam may in part be responsible for the discrepancy between the experiment and the calculations.

Further increase in the THz power is expected from pumping the crystal by one wavelength beam in each arm and/or from switching to shorter, 50 ps CO_2 laser pulses for which the damage threshold should increase by a factor of two in comparison with the 250 ps pulses. It is interesting that the power level of THz radiation generated by a noncollinear phase-matching scheme could be scalable to 100 MW level by increasing the crystal size. A typical beam diameter of the Neptune two-wavelength CO_2 laser system is 12 cm. This beam, in combination with available large-aperture GaAs crystals, opens possibility to create a very high-power source of coherent radiation tunable in the range of 0.1-3 THz.

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