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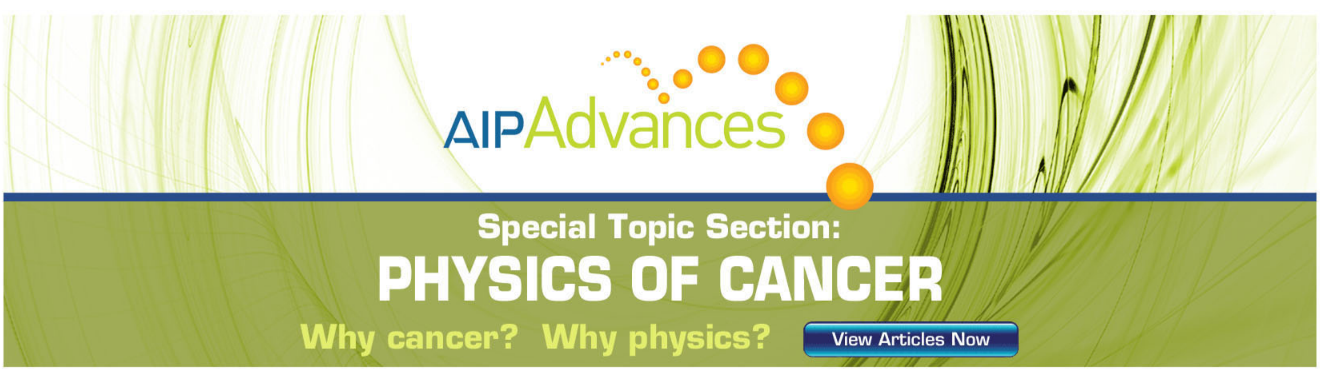

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Power scalability and frequency agility of compact terahertz source based on frequency mixing from solid-state lasers

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We investigate power scalability and frequency agility of a terahertz (THz) source by mixing two frequencies generated by solid-state lasers in a nonlinear crystal. They are made possible by introducing two solid-state laser crystals sharing the same Q switch and output coupler with the same laser beams decoupled to each other by a polarizer. Following the optimization, we have improved the THz output power nearly fivefold at 1.64 THz. By replacing one of the neodymium-doped lithium yttrium fluoride crystals with a neodymium-doped yttrium aluminum garnet crystal, we have produced 2.1 μW at 2.98 THz. © *2011 American Institute of Physics*. [doi:10.1063/1.3572337]

Terahertz (THz) waves have unique applications in chemical sensing[1] and imaging.[2] These applications depend on the availability of compact THz sources. It is obvious that THz quantum cascade lasers have their own advantage due to their compact sizes. Recently, a scheme was implemented for tuning the output wavelengths of THz quantum cascade lasers within a limited range.[3] However, THz quantum cascade lasers must be cryogenically cooled.

On the other hand, solid-state lasers such as those based on neodymium-doped laser crystals can be used to generate very high output powers in the near-infrared region, especially if they are Q-switched.[4] Recently, by mixing the dual-frequency output from a neodymium: yttrium lithium fluoride (Nd:YLF) laser at 286.5 and 284.9 THz in a nonlinear crystal, we generated a THz output at the frequency of 1.643 THz.[5] Since a Nd:YLF laser can be made to be rather compact, such a demonstration opened a new route to a compact THz source. Besides the compactness, such a THz source is operated at room temperature. However, since the two lasing transitions share the same upper level inside in a single Nd:YLF laser crystal,[5] they compete for the output powers. Namely, when the output power at one frequency grows at a higher rate, the power at the other frequency must grow at a lower rate or it can be even saturated. Such a competition severely limits the product of the output powers at the two frequencies, necessary for further scaling up the THz power. Moreover, it causes the instability of the dual-frequency laser output. Furthermore, since such a laser can only emit two specific frequencies, only a single THz output frequency can be generated, which limits the applications of the THz source.

In this letter, we report our results of introducing two laser crystals to generate two different output frequencies. Our experimental result illustrates that the output powers of the solid-state lasers based on two crystals are significantly improved. Consequently, we have improved the THz output power by mixing the two laser frequencies in a nonlinear crystal. After the second laser crystal is introduced, the THz source still maintains its compactness. Moreover, such a configuration can be used to extend to the combinations of different laser crystals for generating different output frequencies.

The experimental setup for the new configuration of laser cavities is shown in Fig. 1. The input mirror 1, polarizer, output coupler make up the first cavity for lasing at 1053 nm while the input mirror 2, polarizer, output coupler make up the second cavity for lasing at 1047 nm. This cavity configuration is completely different from our previous one.[5] Indeed, in the previous work,[5] the Nd:YLF crystal was placed at the arm sharing the 1047 and 1053 nm cavities. As a result, the two radiation beams at 1047 and 1053 nm transition accessed the same population inversion within a single Nd:YLF crystal pumped by the same diode laser. Since the 1047 and 1053 nm beams have perpendicular polarization

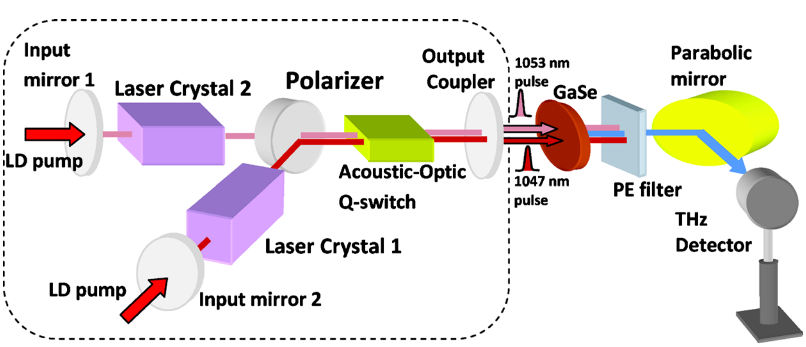

FIG. 1. (Color online) Experimental layout for a configuration of the dual-frequency solid-state laser and compact THz source. The dual-frequency laser cavities are marked by the dashed border line.

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directions, we introduced an intracavity polarizer to separate the two beams into the two cavities. This approach alleviated the gain competition between the 1047 and 1053 nm radiation beams inside the Nd:YLF crystal. However, due to the competition, we observed the unbalanced powers between the two frequencies.[5] In our configuration, we introduced two Nd:YLF crystals (*a*-cut, Nd doped at 1.0%, and $4\times4\times10\ \text{mm}^3$), labeled as laser crystals 1 and 2 in Fig. 1. The two laser crystals were placed at the two divided arms decoupled by the polarizer. As a result, the 1047 nm and 1053 nm transition beams now access the population inversions from two separate gain media, representing an ultimate solution to the gain competition. An acoustic-optic Q-switch was placed at the shared arm of the two laser cavities. Thus, the dual-frequency pulses are synchronized by simultaneously modulating the losses of the two cavities. The other improvement of the cavities is an output coupler shared by the two cavities, i.e., a concave mirror (curvature=15 cm) having a reflectivity of R=75% at both 1047 nm and 1053 nm. Since the dual-frequency beams are emitted from the same output coupler, see Fig. 1, the two beams are collinearly propagating. In order to generate a THz output based on frequency-mixing, we can simply place a nonlinear crystal right after the output coupler. Therefore, the THz source is truly compact.

The two diode pump beams at 808 nm are collimated and focused onto the Nd:YLF crystals through a couple of convex lenses, respectively. The diode pump power can be tuned separately. This feature is quite critical for synchronizing the dual-frequency pulses when the lasers are operated at the pulsed mode. In such a case, the pulse build-up times for the two lasers must be exactly the same. After the acoustic-optic become highly transparent, the laser pulse is not generated instantly. The pulse build-up time is the time it takes to generate the laser pulse when the Q-switch is instantly open. This value is determined by the stimulated emission cross section of the laser gain medium, loss of the cavity, output coupling coefficient, and pumping level above threshold. In fact, once the laser crystals are chosen and the cavity is well aligned, the former three factors cannot be changed. As a result, the only way for changing the pulse build-up time is the pump power level. In our configuration, we can separately change the pump power levels of the two lasers simply by varying the driving currents of the lasers.

When the repetition rate of the Q-switch is set at 5 kHz, we have measured the dependence of the Q-switched output powers on the pump powers at both 1047 and 1053 nm, see Fig. 2. Both of the output powers at 1047 nm and 1053 nm have increased linearly. As a result, we have completely solved the issue of the gain competition in our previous geometry.[5] At the pump power of 10.55 W and 9.55 W, we have obtained the output powers of 2.8 W and 1.918 W at 1047 and 1053 nm, corresponding to net conversion efficiencies of 26.5% and 20.1%, respectively. The corresponding slope efficiencies are 29.8% and 22.5%, respectively. Compared with the previous results,[5] the total output power has been improved by more than twice. In addition, the ratio of slope efficiencies between 1047 and 1053 nm is 1.32. This value is close to the ratio of the corresponding stimulated cross sections (i.e., 1.5).[5]

We have used a 15-mm-long GaSe crystal to measure the THz output by mixing the two laser beams, see Fig. 1. The GaSe crystal is placed directly after the output coupler. This setup is different from our previous one where a beam splitter was used to combine the two dual-frequency beams onto a nonlinear crystal. Obviously, our configuration shown by Fig. 1 is much more compact. We have measured the power dependence, see Fig. 3. At the highest incident power of 4.24 W, we have achieved an output power of 4.464 μW at 1.643 THz (182.4 μm). According to Fig. 3, the dependence is nearly quadratic, which is characteristic for difference frequency generation (DFG). Compared with the previous result, we have increased the output power by 4.7. Such an enhancement is attributed to the improvement of the laser powers at 1047 and 1053 nm. The pulse widths at 1047 nm and 1053 nm are measured to be 17.7 ns and 11.71 ns, respectively. The laser linewidths are measured to be 77.5 GHz and 76.5 GHz, respectively. Assuming the pulse shape is Gaussian, the pulse width of THz radiation is estimated to be 9.766 ns. We have also measured the polarization of the THz radiation as a function of the azimuthal angle of a THz polarizer, shown by inset to Fig. 3. Based on the sinusoidal oscillation, the THz polarization can be determined.

One of the advantages for our configuration lies in the fact that we can generate the THz output frequency simply

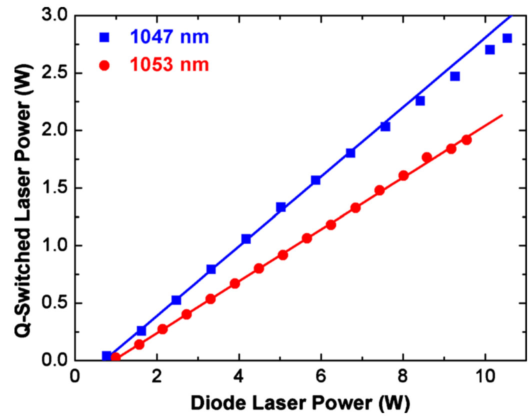

FIG. 2. (Color online) Q-switched output power vs pump power at 1047 and 1053 nm. Dots and squares correspond to data points; straight lines correspond to linear fits to data points.

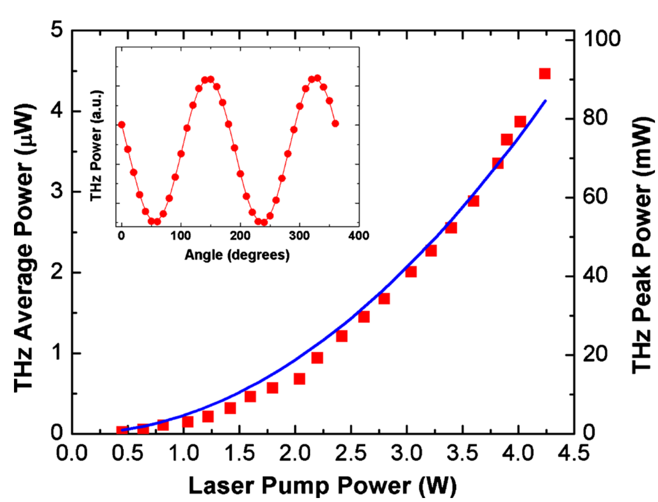

FIG. 3. (Color online) THz average and peak power dependence on the combined power at 1047 and 1053 nm; straight lines correspond to quadratic fits to data points. Inset is the intensity of the THz radiation as a function of the azimuthal angle of a THz polarizer.

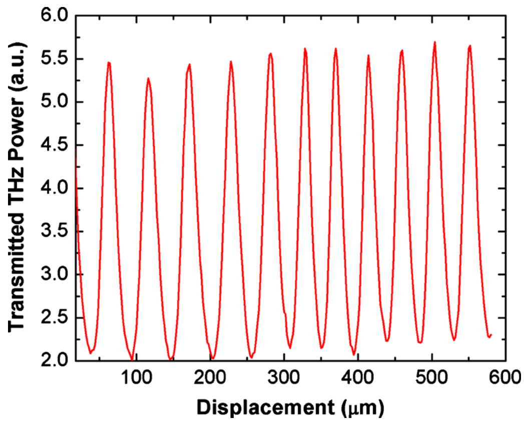

FIG. 4. (Color online) THz power at 100.5 μm, generated by mixing dual frequencies from Nd:YLF and Nd:YAG lasers, being transmitted through a Si etalon as a function of the displacement between two Si wafers.

by choosing two different laser crystals. Since more than 100 Nd-doped laser materials or ceramics have been studied[6] with their wavelengths covering from 1.03 μm to 1.1 μm, it is conceivable for us to generate any THz output wavelength. To demonstrate the frequency agility, we have replaced the Nd:YLF crystal with a 10-mm-long and 1.0%-Nd-doped YAG crystal. All the rest of the optical components remain the same. At the diode pump powers of 9.55 W and 8.653 W, we have generated the output powers of 1.981 W and 1.706 W at 1053 nm and 1064 nm, respectively. At the repetition rate of 5 kHz, the pulse widths are measured to be 9.92 ns and 12.48 ns, respectively. The laser linewidths are measured to be 76.5 GHz and 75.0 GHz, respectively. By mixing the two laser beams on the GaSe crystal, we have generated the THz radiation at 2.983 THz (100.5 μm). The external phase-matching angle for the type II DFG is measured to be 18.3°, which is consistent to the theoretical value.[7] The highest output power is 2.09 μW. The lower output power at such a frequency, compared with that at 1.64 THz, is due to the increased absorption of the THz radiation by the GaSe crystal. The estimated THz pulse width is 7.766 ns. We have measured the THz output wavelength by scanning a Si-based etalon, see Fig. 4. According to Fig. 4, the output wavelength is to be 98 μm, which is close to 100.5 μm, calculated from the two pump wavelengths. The THz linewidth is deduced to be 42 GHz from Fig. 4. This value is close to 53.5 GHz, estimated from the laser linewidths. Using surface-emitting geometry,[8,9] it is feasible for us to extend the output wavelengths to the far-infrared region.

In conclusion, by introducing the second solid-state laser gain medium, we have significantly improved the output powers from the two lasers sharing the same Q switch and output coupler. Consequently, we have improved the THz output power almost fivefold at 1.64 THz. Such a configuration allows us to generate different THz output frequencies by replacing one Nd:YLF laser medium by other solid-state laser crystal. As an example, we have generated an output power of 2.1 μW at 2.98 THz after replacing the Nd:YLF crystal by neodymium-doped yttrium aluminum garnet (Nd:YAG) crystal.

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