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Single-frequency coherent terahertz-wave generation using two Cr:forsterite lasers pumped using one Nd:YAG laser

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We have developed a compact terahertz-wave generator using two small Cr:forsterite lasers with single Nd:YAG laser pumping based on difference frequency generation in a GaP crystal. A Cr:forsterite laser was constructed with diffraction gratings, by which the pulse duration and delay time of the Cr:forsterite laser depend on the Cr:forsterite laser energy and the cavity length. The Cr:forsterite laser energy was tuned using the optical alignment and pumping energy. Temporal overlap of two Cr:forsterite laser pulses was realized at the GaP crystal. A single-frequency terahertz wave was generated at energy of 4.7 pJ around 2.95 THz using a 30-cm-long Cr:forsterite laser system. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2884926]

Terahertz-wave generation was proposed by Nishizawa via phonon excitation or molecular vibration.[1,2] A 12.1 THz wave was later generated with power of 3 W using a GaP Raman laser.[3,4] In 2002, a wide-frequency-tunable terahertz wave was generated based on the difference frequency generation (DFG) of two near-infrared (NIR) lasers in GaP.[5,6] The NIR lasers were a neodymium doped yttrium aluminum garnet (Nd:YAG) laser, an optical parametric oscillator (OPO), and a Cr:forsterite laser. Both OPO and Cr:forsterite lasers can be tuned in the NIR region. With our terahertz-wave generator using Cr:forsterite lasers,[6] double *Q*-switched Nd:YAG lasers are used as pumping Cr:forsterite lasers. In applications, terahertz-wave generation systems have been used for spectroscopic measurement and terahertz imaging.[7–12] A portable terahertz-wave generator is necessary for practical use, by which it can be moved closer to sample for terahertz sensing in the field. For example, in organic and inorganic crystal fabrication processes, crystalline defects can be detected using a terahertz spectrometer.[8,9]

For this study, using only one small 36-cm-long Nd:YAG laser and two Cr:forsterite crystals, we constructed two Cr:forsterite lasers pumped with the YAG laser and generated terahertz waves with the compact device. We investigated the pulse duration and delay time to realize Cr:forsterite lasers which are suitable for use as the terahertz-wave generator because it requires overlapping of two Cr:forsterite laser pulses both temporally and spatially for DFG in GaP.

A Cr:forsterite ($Cr:Mg_2SiO_4$) laser is a solid state laser that is tunable between 1130 and 1370 nm.[13,14] The laser properties have been investigated, leading to the cw and mode-locked pulse operations.[15] A Cr:forsterite crystal has Cr^{4+} in the tetrahedrally coordinated Si^{4+} site, which acts as the lasing ion. Crystal growth processes induce impurities such as Cr^{3+} and Cr^{2+}. Those impurities can be decreased by annealing.[16] Two Cr:forsterite crystals (Cr:F-1, Cr:F-2) with different crystal properties were used for this study: Cr:F-1 is dark blue and Cr:F-2 is dark green. Respectively, they are a rectangular parallelepiped (-R) and a Brewster-cut crystal (-B) of $5\ \text{mm} \times 5\ \text{mm}$ (cross section) $\times 10$ mm (length). Transmittance spectra of Cr:F-1 and Cr:F-2 were measured in the NIR region at room temperature and the absorption coefficient was estimated as shown in Fig. 1, respectively. The absorption peaks at 550, 660, 740, and 1060 nm are attributed to the Cr^{4+}. In contrast, Cr^{3+} has absorption at 474 and 665 nm. At around 700 nm, the Cr^{3+} absorption is dominant compared to that of the Cr^{4+}. The 732 nm absorption is considerably higher than that at 1064 nm, but the slope efficiency excited at 732 nm is less than that at 1064 nm.[17] Consequently, a Nd:YAG laser was used in this study for pumping Cr:forsterite. The figure of merit (FOM) of Cr:F-1 and Cr:F-2 is 8.0 and 5.9, respectively. A *Q*-switched Nd:YAG laser with 10 ns pulse duration at 10 Hz repetition was used to pump the Cr:forsterite crystals. Selective frequency cavity oscillator systems were constructed using the Cr:F-1 and Cr:F-2. The Cr:forsterite laser characteristics of the pulse duration and delay time were measured in terms of the Cr:forsterite laser energy and cavity length. A terahertz-wave generation system was constructed using two Cr:forsterite crystals and one *Q*-switched Nd:YAG laser.

A plane-plane cavity oscillator was constructed for measurement of the slope efficiency in the Cr:forsterite laser. The output coupler is of 6% transmittance around 1.2 μm. The Cr:forsterite laser energies using Cr:F-1-B, Cr:F-1-R, and Cr:F-2-B were measured according to changes in the Nd:YAG laser energy. Cr:F-1-B has the highest slope efficiency of 8.4%, with the lasing threshold of 2.2 mJ/mm^2. Slope efficiencies and lasing thresholds are, respectively, 6.8% and 2.0 mJ/mm^2 in Cr:F-1-R, and 4.8% and 4.6 mJ/mm^2 in Cr:F-2-B. These results suggest a relationship of the slope efficiency to FOM and the crystal shape.

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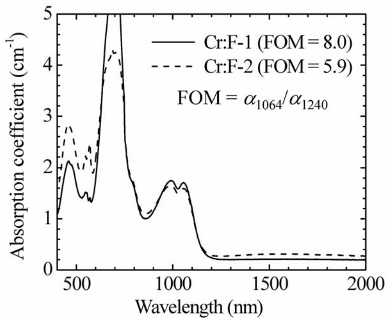

FIG. 1. Absorption coefficients of Cr:F-1-R and Cr:F-2-R in the near-infrared region.

It is necessary to select a frequency for terahertz-wave generation. The cavity oscillator using a diffraction grating can select a frequency. The selective frequency cavity was adjusted so that the first-order reflected light is directed to the direction of incident beam. The cavity can oscillate at 1250 nm when the incident beam angle is 31.2° normal to the grating of 830 lines/mm. The selective frequency Cr:forsterite laser can be outputted from zero-order light. The pulse duration and delay time were measured as a function of Cr:forsterite laser energy and cavity length. The laser crystal was Cr:F-1-R. The delay time was measured as the time from the 50% rising edge of the Nd:YAG laser to the 50% rising edge of the Cr:forsterite laser using photodiodes and an oscilloscope. The 200 points were recorded at the same optical condition; each result was plotted and fitted to a Gaussian function for measurement of the pulse duration and delay time.

Figure 2 shows the Cr:forsterite laser characteristics of the pulse duration and delay time when the cavity length was fixed at 20 cm. The Nd:YAG pumping laser energy is changed to 66, 80, and 95 mJ. Changing the optical alignment at each Nd:YAG laser pumping energy changed the Cr:forsterite laser energy to maximum. Both the pulse duration and delay time decreased when the Cr:forsterite laser energy increases.

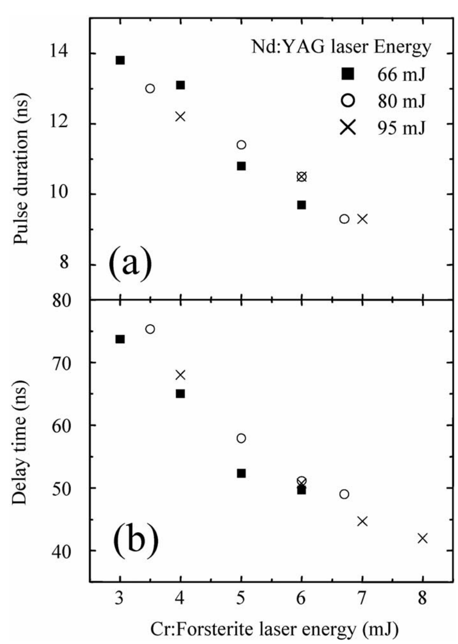

FIG. 2. Cr:forsterite laser characteristics of the pulse duration (a) and delay time (b) at Cr:forsterite laser energy of 3–8 mJ. The Nd:YAG laser power was changed to 66, 80, and 95 mJ. The cavity length was fixed to 20 cm.

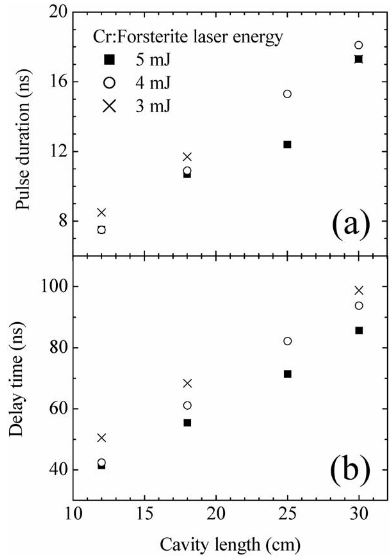

FIG. 3. Cr:forsterite laser characteristics of the pulse duration (a) and delay time (b) with the cavity length of 12–30 cm. The Cr:forsterite laser energies were 3, 4, and 5 mJ.

Figure 3 shows the Cr:forsterite laser characteristics of the pulse duration and delay time for the case in which the cavity length was changed from 12 to 30 cm at Cr:forsterite laser energies of 3, 4, and 5 mJ. Both the pulse duration and delay time increased as a function of the cavity length. The result of pulse duration at any cavity length can be understood according to the photon lifetime, which is

$$\tau = \frac{2L}{c(1-R)},$$

where τ is the photon lifetime, L is the cavity length, c is the velocity of light, and R is the transmittance of an output coupler. Therefore, the cavity length produces a long photon lifetime and long pulse duration.

According to these results, the delay time can be controlled according to the Cr:forsterite laser energy and cavity length. The Cr:forsterite laser energy is controllable according to the conversion efficiency and pumping energy. The conversion efficiency is changed by optical alignment. Each pumping energy of the two Cr:forsterite lasers can be changed using a pair of a polarizer and a half-wavelength plate even if a single Nd:YAG laser is used. The method can generate a higher-powered terahertz wave because the two laser conversion efficiencies are kept high.

Figure 4 shows that two Cr:forsterite laser oscillators with a 15 cm cavity for terahertz-wave generation were constructed to be 30×30 cm^2. The 36-cm-length Nd:YAG laser can be put diagonally under this Cr:forsterite laser system. The two different frequency lasers were generated using, respectively Cr:F-1-R and Cr:F-2-R with single Nd:YAG pumpings of 95 and 105 mJ. The Cr:forsterite laser using the Cr:F-1-R crystal energy is 5.0 mJ; the frequency is tuned to around 1238.4 nm. The Cr:forsterite laser using the Cr:F-2-R crystal energy is 1.5 mJ and the frequency is 1223.5 nm. The two pulses are overlapped temporally and spatially at the

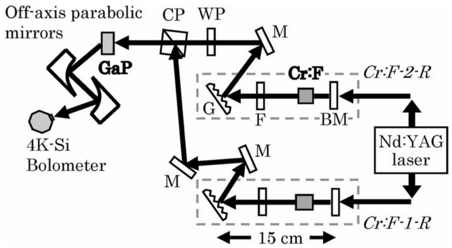

FIG. 4. Schematic of optical setup used for terahertz-wave generation with two Cr:forsterite lasers. CP: cubic polarizer; WP: half-wavelength plate; M: mirror; G: grating; BM: $T=95\%$ at 1064 nm and $R=99.7\%$ around 1.2 μm back mirror; F: 1064 nm cutoff long-wavelength pass filter.

GaP crystal surface. The pulse timing was tuned using the conversion efficiency of the Cr:forsterite laser. The terahertz wave was generated with energy of 4.7 pJ around 2.95 THz. Both the Cr:forsterite laser linewidths were measured as less than 0.07 nm using a spectrum analyzer. The linewidth of the generated terahertz wave is estimated as less than 30 GHz.

In conclusion, changing the conversion efficiency and pump energy of a Cr:forsterite laser controlled the temporal overlap of two Cr:forsterite laser pulses. A terahertz wave was generated using two Cr:forsterite lasers pumped using a single Nd:YAG laser. The Cr:forsterite laser system was built as 30 cm^2 for portable use in the field.

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[1] J. Nishizawa, Denshi Kagaku **14**, 17 (1963) (in Japanese).
[2] J. Nishizawa, Denshi Gijutsu **7**, 101 (1965) (in Japanese).
[3] J. Nishizawa and K. Suto, J. Appl. Phys. **51**, 2429 (1980).
[4] K. Suto and J. Nishizawa, IEEE J. Quantum Electron. **QE-19**, 1251 (1983).
[5] T. Tanabe, K. Suto, J. Nishizawa, K. Saito, and T. Kimura, Appl. Phys. Lett. **83**, 237 (2003).
[6] K. Suto, T. Sasaki, T. Tanabe, K. Saito, J. Nishizawa, and M. Ito, Rev. Sci. Instrum. **76**, 123109 (2005).
[7] J. Nishizawa, J. Phys. Soc. Jpn. **57**, 163 (2001).
[8] J. Nishizawa, K. Suto, T. Sasaki, T. Tanabe, T. Tanno, Y. Oyama, and F. Sato, Proc. Jpn. Acad., Ser. B: Phys. Biol. Sci. **82**, 353 (2006).
[9] J. Nishizawa, T. Sasaki, Y. Oyama, and T. Tanabe, Physica B **401–402**, 677 (2007).
[10] X.-C. Zhang, Phys. Med. Biol. **47**, 3667 (2002).
[11] D. R. Grischkowsky and D. Mittleman, in *Sensing with Terahertz Radiation*, edited by D. Mittleman (Springer, Berlin, 2003), Vol. 85, pp. 1–38.
[12] See Special Issue on *T-Ray Imaging, Sensing, and Detection*, edited by D. Abbott and X.-C. Zhang, Proc. IEEE **95**, 1505 (2007).
[13] V. Petričević, S. K. Gayen, R. R. Alfano, K. Yamagishi, H. Anzai, and Y. Yamaguchi, Appl. Phys. Lett. **52**, 1040 (1988).
[14] K. V. Yumashev, N. V. Kuleshov, P. V. Prokoshin, A. M. Malyarevich, and V. P. Mikhailov, Appl. Phys. Lett. **70**, 2523 (1997).
[15] For example, A. Sennaroglu, Prog. Quantum Electron. **26**, 287 (2002).
[16] T. Yamazaki, S. Nakai, Y. Anzai, and Y. Aoki, J. Jpn. Assoc. Cryst. Growth **32**, 334 (2005).
[17] Z. X. Jiang, I. T. McKinnie, L. A. W. Gloster, and T. A. King, Pure Appl. Opt. **5**, 77 (1996).