Efficient high-power terahertz beating in a dual-wavelength synchronously mode-locked laser with dual gain media

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We originally present a novel tactic to accomplish a compact efficient dual-wavelength synchronously mode-locked laser by physically combining the $Nd:YVO_4$ crystal to the $Nd:GdVO_4$ crystal as a composite gain medium. With the developed method, the total output power at 1.06 μm could be effectually produced to reach 1.3 W under the optimally balanced two-color intensities. The corresponding mode-locked pulse width and repetition rate are measured to be 47 ps and 2.86 GHz, respectively. Through the optical beating between two carrier frequencies of dual-color synchronous pulses, a train of 0.32 THz ultrashort pulses is further generated with the effective duration of down to 1.6 ps.

OCIS codes: (140.4050) Mode-locked lasers; (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium; (140.3580) Lasers, solid-state.

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Dual-wavelength synchronously mode-locked lasers are attractive for many applications, such as pump-probe measurement, spectroscopic study, generation of ultrahigh repetition rate pulses through optical beating, and so on. Such light sources are also desirable for producing coherent terahertz (THz) radiation by difference frequency generation, which is recognized as a powerful tool in scientific studies as well as military fields because of its unique optical properties [1–3]. To date, dual-wavelength synchronously mode-locked solid-state lasers around 1 μm relied mainly on the use of the disordered or mixed crystals possessing multiple sharp fluorescent lines with comparable spectral intensities [4–10]. However, their output power ratios between each emission line were relatively difficult to be controlled for obtaining the balanced two-color intensities. Therefore, it is practically valuable to develop a convenient and straightforward approach for readily achieving a dual-wavelength laser with equalized output emissions.

Recently, the combination of the Kerr lens and thermal-lensing effects was exploited to fulfill a compact reliable self-mode-locked operation in various diode-pumped solid-state laser systems with multi gigahertz (GHz) pulse repetition rates [11–13]. In this Letter, we originally design a compact dual-wavelength picosecond diode-end-pumped Nd-doped vanadate laser with the self-mode locking. The novelty is that the $Nd:YVO_4$ and $Nd:GdVO_4$ crystals are physically combined as a composite gain medium for simultaneous two-color emission at 1064 and 1063 nm. It is experimentally found that the output power ratio between the 1064 and 1063 nm lines could be flexibly controlled in the range of 0.15–10 simply by varying the waist position of the pump beam. Under an incident pump power of 14 W, this miniature picosecond laser could be readily optimized to realize the balanced dual-wavelength intensities for effectually generating the total output power of 1.3 W at 1.06 μm. The corresponding mode-locked pulse duration and repetition rate are measured to be 47 ps and 2.86 GHz, respectively. We also experimentally found that the perfect temporal overlapping between the dual-color pulses leads the autocorrelation trace to exhibit a strong interference fringe with full modulation, in which a train of optically beat pulses with the ultrahigh pulse repetition rate of 0.32 THz is effectually produced with the effective duration as short as 1.6 ps. By combining two active media with proper wavelength separation, it is believed that the proposed method here is a promising way to generate a series of optically beat subpicosecond pulses with the THz repetition rate. For example, if the $Nd:YVO_4$ and Nd:YLF crystals with emission lines of 1064 and 1047 nm are chosen, the ultrahigh repetition rate of 4.58 THz could be generated with the help of the optical beating.

The experimental configuration for our diode-end-pumped dual-wavelength synchronously self-mode-locked Nd-doped vanadate laser is schematically shown in Fig. 1. A plano–concave mirror with the radius of curvature of 1000 mm was used as the input mirror. It was coated for antireflection at 808 nm on the plane side and

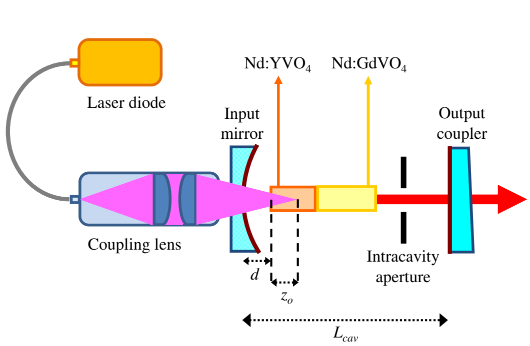

Fig. 1. Experimental configuration for the diode-end-pumped dual-wavelength synchronously self-mode-locked Nd-doped vanadate laser.

was coated for high transmission at 808 nm and high reflection at 1064 nm on the concave side. The composite active medium was made up of two vanadate laser materials. The first one was an a-cut $Nd:YVO_4$ crystal with the doping concentration of 0.2% and the length of 5.5 mm, and it was closely followed by an a-cut $Nd:GdVO_4$ crystal with the doping concentration of 0.5% and the length of 8 mm. The $Nd:GdVO_4$ crystal was physically contacted with the $Nd:YVO_4$ crystal as close as possible. The crystallographic c axis of the $Nd:GdVO_4$ crystal was aligned to be parallel to that of the $Nd:YVO_4$ crystal. The transverse cross section for both gain media were 3 mm × 3 mm. All end faces of the Nd-doped vanadate crystals were coated to be antireflective at the pump and lasing wavelengths. The composite gain medium was wrapped with indium foil and mounted in a water-cooled copper holder with a temperature of 16°C. The pump source was a 16 W 808 nm fiber-coupled laser diode with a core diameter of 200 μm and a NA of 0.22. In order to make the pump absorption of the $Nd:YVO_4$ crystal to be around 50%, the emission wavelength of the laser diode was intentionally tuned to 805 nm instead of the strongest absorption peak at 808 nm. The residual pump light was subsequently absorbed by the followed $Nd:GdVO_4$ crystal. A pair of the plano–convex coupling lenses with the focal lengths of 25 mm and the total coupling efficiency of 88% was utilized to reimage the pump beam into the composite gain medium with the pump radius of approximately 120 μm. Taking into account of the coupling efficiency, the maximum incident pump power in our experiment is approximately 14 W. The unit of the coupling lenses was placed on a linear translation stage to adjust the waist position of the pump light through the parameter z_o, which is defined as the distance from the entrance face of the $Nd:YVO_4$ crystal to the waist location of the pump beam inside the composite gain medium, as indicated in Fig. 1. A flat wedged mirror with the reflectivity of 95% at 1064 nm was employed as the output coupler, which was experimentally found to give the best performance in output power. The geometrical length of laser cavity L_{cav} was set to be 36 mm for obtaining a compact reliable self-mode-locked laser. Considering the refractive indices of the laser materials, the optical cavity length was calculated to be approximately 52.5 mm, corresponding to the fundamental pulse repetition rate of 2.86 GHz. By controlling the number of the longitudinal modes via the spatial hole burning effect [14], the separation between the input mirror and the $Nd:YVO_4$ crystal d was fixed to be 8 mm for acquiring comparable mode-locked pulse durations at 1064 and 1063 nm. An intracavity aperture was inserted inside the resonator to ensure the fundamental transverse mode oscillation.

A Fourier optical spectrum analyzer (Advantest, Q8347), which is constructed with a Michelson interferometer, was used to record the spectral information of the laser output with a resolution of 0.003 nm. The real-time temporal behavior of the mode-locked pulses was monitored by a high-speed InGaAs photodetector with the rise time of 35 ps, and the received signal was sent to a digital oscilloscope (Agilent, DSO 80000) with the electrical bandwidth of 12 GHz and the sampling interval of 25 ps. The output signal of the photodetector was also delivered to a RF spectrum analyzer (Advantest, R3265A) with the bandwidth of 8 GHz. The fine structure of the mode-locked pulses was measured with the help of a commercial autocorrelator (APE pulse check, Angewandte Physik and Elektronik GmbH).

First of all, finely tilting the composite gain medium and carefully adjusting the cavity alignment could make our Nd-doped vanadate laser be in a stable continuous-wave mode-locked state, as observed in our previous works [11–13]. Then, we varied the waist position of the pump beam along the optical axis of the resonator to control the output powers radiated from the $Nd:YVO_4$ and $Nd:GdVO_4$ crystals, whose emission wavelengths are well known to correspond to 1064 and 1063 nm, respectively. It is experimentally found that the output power ratio $P_{1064\ \mathrm{nm}}/P_{1063\ \mathrm{nm}}$ could be flexibly altered from 10 to 0.15 when z_o was continuously increased from 0 to 5 mm. Figure 2 illustrates the dependence of the total output power at 1.06 μm on the incident pump power under the optimally balanced dual-wavelength intensities, corresponding to the case for $z_o = 3.9$ mm. At an incident pump power of 14 W, the maximum total output power as high as 1.3 W is generated with our compact dual-wavelength mode-locked Nd-doped vanadate laser. The optical spectrum for balancing the two-color output powers at an incident pump power of 10.3 W is depicted in Fig. 3. It can be seen

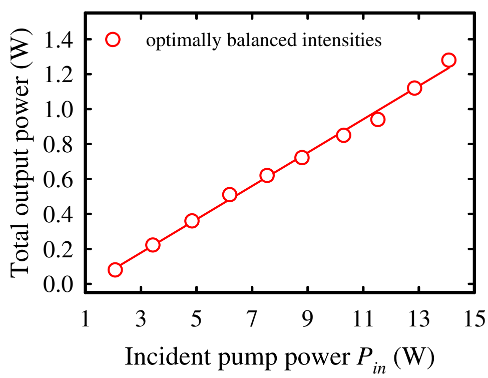

Fig. 2. Dependence of the total output power at 1.06 μm on the incident pump power under the optimally balanced dual-wavelength intensities, corresponding to the case for $z_o = 3.9$ mm.

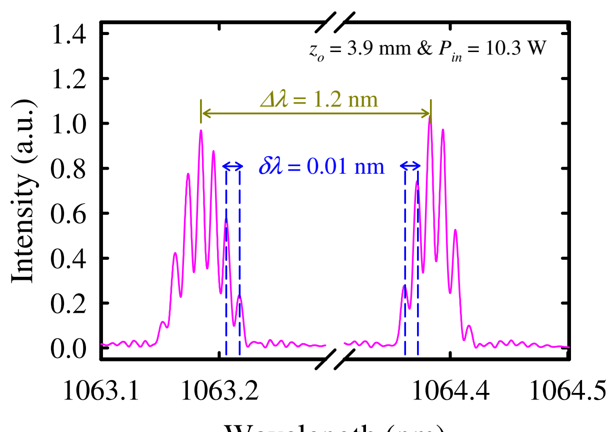

Fig. 3. Optical spectrum for the dual-wavelength mode-locked laser at $z_o = 3.9$ mm.

that the central wavelengths for each spectral band are located at 1063.18 and 1064.38 nm with the same FWHM of about 0.05 nm. Besides, the longitudinal mode spacing $\delta\lambda$ of 0.01 nm is in agreement with the theoretical value deduced from the fundamental pulse repetition rate δf of 2.86 GHz. The deduction is based on the relation $\delta\lambda = (\lambda^2/c)\cdot\delta f$, where $\delta\lambda$ is the longitudinal mode spacing, λ is the central wavelength, c is the velocity of light, and δf is the free spectral range equal to the pulse repetition rate of the mode-locked laser.

Typical oscilloscope traces of the dual-wavelength mode-locked pulses are illustrated in Figs. 4(a) and 4(b) with the time span of 200 and 5 ns, respectively. Figure 4(a) illustrates the amplitude stability of the laser, and the fluctuation is experimentally found to be better than 2%. On the other hand, the pulse period of 350 ps in Fig. 4(b) agrees well with the round-trip time determined by the optical cavity length of 52.5 mm. More importantly, the absence of the multiple pulses in a round-trip time scale verifies that our dual-wavelength self-mode-locked laser is in a reliable and perfect synchronization status. The RF spectra for the two-color mode-locked Nd-doped vanadate laser are displayed in Figs. 5(a) and 5(b). Figure 5(a) describes the fundamental harmonic at 2.86 GHz and the second harmonic at 5.72 GHz, which are consistent with the experimental results shown in Figs. 3 and 4. The deduction is based on the fact that the first harmonic of 2.86 GHz is in agreement with the longitudinal mode spacing of 0.01 nm and the pulse period of 350 ps. Moreover, it can be seen that the peak of the fundamental harmonics is 50 dBc above the background level, and the relaxation oscillation sidebands are negligibly observable. To quantitatively characterize the stability of the laser, we calculate the relative frequency deviation of the fundamental harmonic $\Delta\nu/\nu$, where ν is the central frequency and $\Delta\nu$ is the FWHM of the fundamental harmonic, respectively. Referring to Fig. 5(b), the value $\Delta\nu/\nu$ is estimated to be around 10^{-4} over an hour-long operation, which means a nice long-term stability.

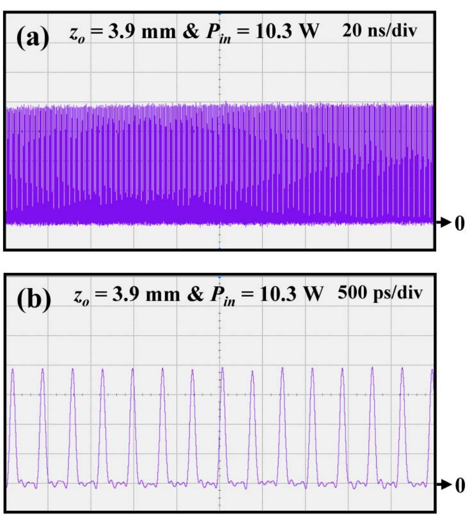

Fig. 4. Oscilloscope traces with the time span of (a) 200 ns and (b) 5 ns for the dual-wavelength mode-locked laser at $z_o = 3.9$ mm.

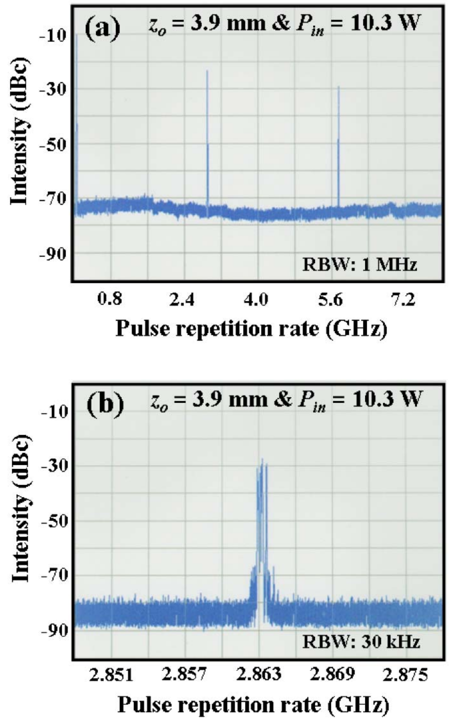

Fig. 5. RF spectra with the frequency span of (a) 8 GHz and (b) 30 MHz for the dual-wavelength mode-locked laser at $z_o = 3.9$ mm.

Figure 6(a) reveals the autocorrelation trace of the two-color mode-locked laser with the delay time of 200 ps. The FWHM of the autocorrelation trace is measured to be about 68 ps. Assuming the temporal intensity to follow the Gaussian-shaped profile, the pulse duration could thus be evaluated as 47 ps. Furthermore, a strong interference fringe with the modulation depth of nearly 100% is observed in the autocorrelation trace as a result of the optical beating between two carrier frequencies of the dual-wavelength mode-locked pulses, that is, 1063.18 and 1064.38 nm. The complete modulation confirms that the perfect temporal overlapping is accomplished between the dual-wavelength mode-locked pulses. The detailed characteristic of the interference fringe pattern is depicted in Fig. 6(b) with the delay time of 10 ps. The optical beat frequency of 0.32 THz could be deduced from the pulse period of 3.1 ps and it agrees with the wavelength separation $\Delta\lambda$ of 1.2 nm of the two central spectral bands measured in Fig. 3. In terms of the cosine-like pulse shape, the effective pulse width of the optically beat wave could be inferred to exactly correspond to the FWHM duration of the experimentally measured autocorrelation trace [15]. As a result, the effective pulse duration is calculated to be as short as 1.6 ps, significantly shorter than the original Gaussian-shaped pulse of 47 ps. Based on the experimental results, it is believed that the observation of the optical beating in our developed dual-wavelength mode-locked laser is potentially beneficial for generating a series of subpicosecond ultrashort pulses with the THz repetition rate. Moreover, compared with the THz quantum cascade lasers that must be cryogenically cooled [16], the concept presented here is a more practical means for generating

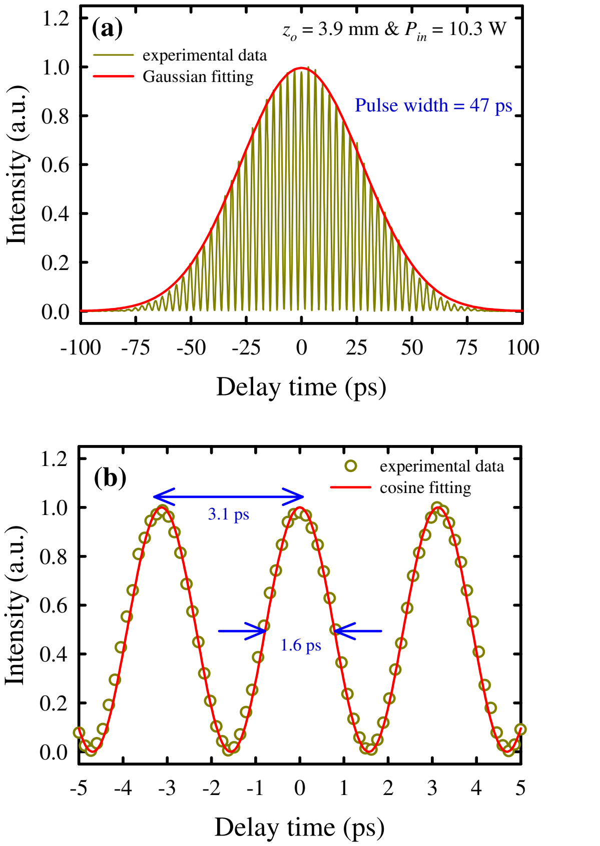

Fig. 6. Autocorrelation traces with the delay time of (a) 200 ps and (b) 10 ps for the dual-wavelength mode-locked laser at $z_o = 3.9$ mm.

THz optical wave via nonlinear frequency conversion based on the GaSe, GaP, and $ZnGeP_2$ crystals [17,18].

In summary, a novel approach has been successfully developed for efficiently generating dual-wavelength emissions in a diode-end-pumped self-mode-locked Nd-doped vanadate laser. We have compactly joined the Nd:YVO_4 crystal to the Nd:$GdVO_4$ crystal to form a composite gain medium able to simultaneously emit 1064 and 1063 nm lines. By suitably adjusting the waist position of the pump beam inside the gain medium, the total output power of up to 1.3 W has been readily generated for the optimally balanced dual-color intensities with the mode-locked pulse width of 47 ps and repetition rate of 2.86 GHz. Experimental measurements on the autocorrelation trace further reveal that the excellent synchronization between the dual-wavelength pulses enables us to acquire a train of optically beat pulses with the 1.3 ps pulse duration and 0.32 THz repetition rate. The proof-of-principle experiment demonstrated in this work clearly shows the large feasibility of our developed dual-wavelength synchronously mode-locked light source to be employed in a great number of practical applications. An in-depth theoretical analysis for this highly compact dual-wavelength mode-locked solid-state laser is underway and will be presented later.

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