Multiple-color cw visible lasers by frequency sum-mixing in a cascading Raman fiber laser

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Abstract: Multiple cw visible lasers at wavelengths ranging from 550nm to 625nm were generated by intracavity frequency sum-mixing of a cascading Raman fiber laser in a type-I noncritically phase-matched lithium triborate crystal. The phase matching conditions for individual wavelengths were realized by tuning the temperature of the lithium triborate crystal.

OCIS codes: (140.3510) Lasers, fiber; (140.3550) Lasers, Raman; (140.7300) Visible lasers

References and links

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#4136 - $15.00 US Received 30 March 2004; revised 14 April 2004; accepted 14 April 2004

1. Introduction

Coherent cw light sources in visible region are of great importance for applications in metrology, remote sensing, medicine, and display, etc. [1]. Diode-pumped Nd-doped solid-state lasers can operate efficiently in blue, green, and red spectral regions by frequency doubling. However, the wavelength region from 550 to 650 nm was difficult to cover for the absence of fundamental lasers that can operate efficiently there. Several approaches have been used to generate the all-solid-state source in the yellow-orange wavelength region: solid dye lasers [2], frequency doubling of crystal Raman lasers [3] or $LiF:F_2^-$ laser [4], and sum-frequency mixing of two Nd laser lines at 1064nm and 1319nm [5]. Besides, there is considerable interest in generating multiple visible lasers from a single compact laser system. For example, such kind of systems had been demonstrated by frequency doubling and frequency sum mixing of $Nd^{3+}:YVO_4$ lasers in periodically or aperiodically poled $LiTaO_3$ [6, 7], and crystal Raman lasers [8].

In this paper we report the generation of multiple cw visible lasers at 550nm, 569nm, 589nm, 606.5nm, and 625nm by intracavity frequency sum mixing of a cascading Raman fiber laser in a type-I noncritically phase matched lithium triborate (LBO) crystal. The phase matching conditions for the 569nm, 589nm, and 606.5nm laser were realized in the experiments by tuning the temperature of LBO crystal to the vicinity of 70°C, 40°C, and 20°C, respectively.

2. Experimental setup

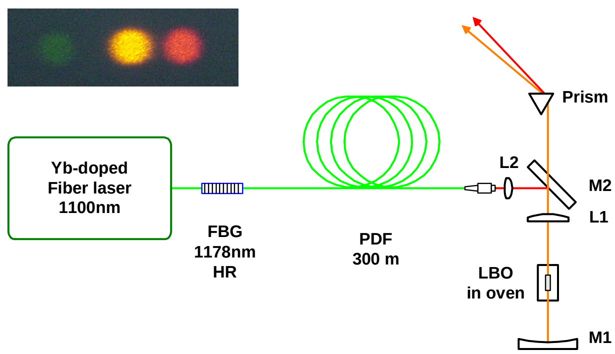

Fig. 1 Schematic of the experimental setup. Cavity is formed by FBG, M1. M2 is a dichroic mirror through which visible lights escape from the cavity. Inset is a picture of dispersed visible emission (from left to right, 569nm, 589nm, and 606.5nm) when temperature is tuned to near 30°C, where all frequency sum-mixing channels are off the phase-match condition so that the intensities of these emissions were comparable.

Schematic of experimental setup is shown in Fig. 1. An Ytterbium-doped double-clad fiber laser with a Flexcor-1060 single mode fiber output at 1100nm was used as pump source. The initial motivation of the study is to generate 589nm laser by the frequency doubling of a 1178nm Raman fiber laser for the possible application in Sodium laser guided star [9, 10] and spectroscopy. So the experimental setup is designed for this purpose. The pump source fiber end was spliced to a fiber Bragg grating (FBG) (reflectivity >99% at 1178nm and bandwidth of 1.2 nm). Since both the pump fiber and FBG are made of the Flexcor-1060 fiber, a very low loss splicing was achieved between them. The Raman gain fiber was a 300-m-long phosphorous-doped single-mode optical fiber (PDF), which had 12mol % of P_2O_5 and a refractive index difference between the core and the clad of 0.0107. A small mismatch in the

#4136 - $15.00 US
Received 30 March 2004; revised 14 April 2004; accepted 14 April 2004

mode field diameters of PDF and the Flexcor-1060 fiber resulted in a splicing loss of only about 0.2 dB between them. Aspheric lens L2 (focal length: 8 mm) was used to collimate the light from PDF. The beam was focused once again into a LBO crystal using lens L1 (focal length 50 mm). Both lenses were coated with antireflecting coating for 1178 nm. Frequency doubling was achieved in a type-I noncritically phase-matched LBO ($3\times3\times20mm^3$) mounted in an oven with temperature control. Concave mirror M1 (50-mm radius of curvature and HR at around 1178 nm) was used as the end-mirror. The dichroic mirror M2 (highly reflecting at 1178nm and transmitting at 589 nm) was used as output coupler for the 589 nm light. The visible light escaping from the cavity through M2 was separated from infrared radiation leaking through M2 by a Brewster prism. Spectra of the output were measured with an AQ-6315A optical spectrum analyzer (ANDO Co.) directly after the dichroic mirror M2.

3. Results

Threshold as low as 1.8W was realized for the 1178nm laser. $602cm^{-1}$ Raman shift is required to convert 1100nm to 1178nm light. The Raman gain at $602cm^{-1}$ is not the peak value. There are two peaks in the Raman scattering spectrum of PDF, one is at $1330cm^{-1}$ which is sharp and due to oxygen double-bonded to P atoms, the other is at $490cm^{-1}$ which is broad and due to oxygen double bonded to Si atoms [11]. When the pump power increased to about 6.5W, 1250.5nm laser reached the threshold too, which is a Stokes shift from 1178nm by $490cm^{-1}$. Fig.2 (left) shows the emission spectra at pump power of 5.6W and 11W, respectively. The feedback for 1250.5nm is from the nonzero reflection of the free space optics (at the level of tens percentage according to transmission data provided by company) at one end and the Fresnel reflection of the fiber end at other end. Outcoupling for 1178nm laser is very low, so intracavity intensity of 1178nm laser is expected high. Consequently, Raman gain at 1250.5nm is very high, so it can lase in spite of the lossy resonator. Emergence of high order Stokes lasers was also observed in experiments on fundamental lasers[12], where the feedback for 1250.5nm laser is from the Fresnel reflection of fiber end at both ends.

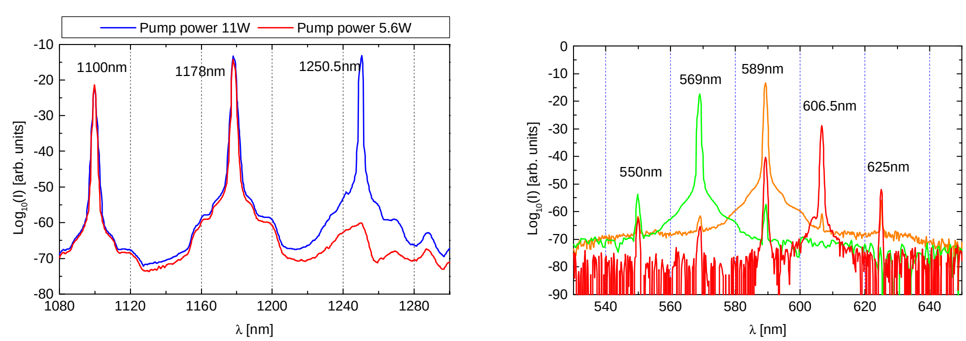

Fig. 2 (left) The emission spectra at the near-infrared wavelength range at pump power of 5.6W and 11W, respectively. (right) typical emission spectra at visible wavelength range when the temperature of LBO crystal was tuned to 70°C (dash line), 40°C (solid line), and 20°C (dot line), which correspond to phase matching condition for 569nm, 589nm and 606.5nm generation, respectively.

Intracavity frequency conversion was used with the aim of increasing efficiency in mind. The LBO crystal was cut at $\theta = 90°$ and $\phi = 0°$. With such a cut configuration, phase match condition for type-I second harmonic generation (SHG) can be obtained over a wide wavelength range by tuning the crystal temperature [13]. Calculated by SNLO [14], type-I noncritical phase match condition for SHG of 1178nm can be realized near 40°C with effective nonlinear coefficient $d_{eff} = 8.39\times10^{-1}$ pm/V and good temperature, bandwidth, and acceptance

#4136 - $15.00 US
Received 30 March 2004; revised 14 April 2004; accepted 14 April 2004

angle tolerances. The advantage of noncritical phase matching is the absence of walk-off of the laser beams, so one can use a long crystal to obtain higher conversion, and the laser quality will not be degraded. The LBO crystal was mounted near the beam waist, which was measured to be about 40μm, smaller than the optimum waist of 57μm for a nonlinear crystal of length 20mm and the fundamental light wavelength of 1178nm according to Boyd and Kleinman [15]. But based on their theory the focusing parameter is not very critical, it is expected that the efficiency is within 10% of that for optimum focusing.

Figure 2 (right) shows a typical spectrum of the visible output when temperature was tuned to 40°C. Interestingly, one can find beside strong emission at 589nm, there are lines at 550nm, 569nm, 606.5nm, and 625nm, which correspond to frequency mixing of 1100nm + 1100nm, 1100nm + 1178nm, 1178nm + 1250.5nm, and 1250.5nm + 1250.5nm, respectively. All possible mixing channels are calculated with SNLO [14], results are shown in Tab.1. Phase matching condition can be achieved for all frequency-mixing channels by tuning the temperature from 107°C to 6°C, while the effective nonlinear coefficient decreases slightly when the wavelength increases.

Table 1 Calculated phase matching temperature and effective nonlinear coefficient for all frequency sum-mixing channels

Mix channel (nm)	1100 + 1100	1100 + 1178	1100 + 1250.5	1178 + 1178	1178 + 1250.5	1250.5 + 1250.5
λ_v (nm)	550	569	585	589	606.5	625
T(°C)	107	70	44	40	20	6
$d_{eff}(\times 10^{-1}$pm/v)	8.46	8.42	8.39	8.39	8.35	8.32
Power (mW)		6		10	0.2	

In the experiments, we had also tuned the temperature to the phase matching condition of about 70°C and 20°C for the process of 1100nm + 1178nm $\rightarrow$ 569nm and 1178nm + 1250.5nm$\rightarrow$ 606.5nm. Corresponding emission spectra are also shown in Fig. 2 (right). Frequency doubling of the pump laser 1100nm + 1100nm $\rightarrow$ 550nm is of no interest, so it was not investigated. The process of 1250.5nm + 1250.5nm $\rightarrow$ 625nm is of interest, however the phase matching temperature of 6°C was not possible to reach in the experiments. 1100nm + 1250.5nm $\rightarrow$ 585nm is interesting, but it is weak and near the strong 589nm emission we didn't observe in the experiments.

Figure 3 shows the 589nm laser output as a function of the pump power. Just above the threshold, the output of 589nm laser increased nonlinearly with the pump power, because of the square law dependence of the conversion efficiency on the fundamental laser intensity, but was soon saturated. The maximum output at 589 nm obtained was about 10mW. The saturation of the output is mainly due to the emergence of higher order Stokes Raman lasers. We had also investigated bright emission at 569nm and 606.5nm at the phase matching condition. The output power as a function of the pump power is shown in Fig. 4. Up to 6mW and 0.2mW of the 569nm and 606.5nm laser were obtained, respectively.

The mixing efficiencies are low (lower than 0.1%), which results from the broad linewidth of the Raman lasers. Both 1178nm and 1250.5nm lines were broadened at higher pump power due to the broad Raman spectrum and high intracavity power. At the saturation stage the typical linewidth of 1178nm and 1250.5nm are about 2nm and 1.5nm, respectively. The linewidth of 589nm, 569nm, and 606.5nm are all at the level of 0.7nm. Another reason is the random polarization of the fundamental Raman fiber laser, so only half of the power is useful.

Using narrower FBG at 1178nm and at the wavelength of higher order Raman shift may narrow the linewidth of the Raman lasers. In present experiments the bandwidth of the 1178nm

#4136 - $15.00 US Received 30 March 2004; revised 14 April 2004; accepted 14 April 2004

FBG is about 1.2nm. The feedback for the higher order Raman laser is the Fresnel reflection at fiber end and dielectric mirror, both of which are frequency-insensitive. Highly reflective FBG of bandwidth 0.1~0.2nm at 1μm region is available, so there is potential in this scheme to increase the efficiency.

Another potential scheme is a master oscillator power amplifier (MOPA): use seeds of narrow bandwidth at requested wavelengths and amplify them in fiber by Raman gain. Multiple lasers of narrow bandwidth may be obtained in proper design. After that, specially designed periodically poled nonlinear crystals like PPLN and PPKTP can be used to convert these lasers to visible externally.

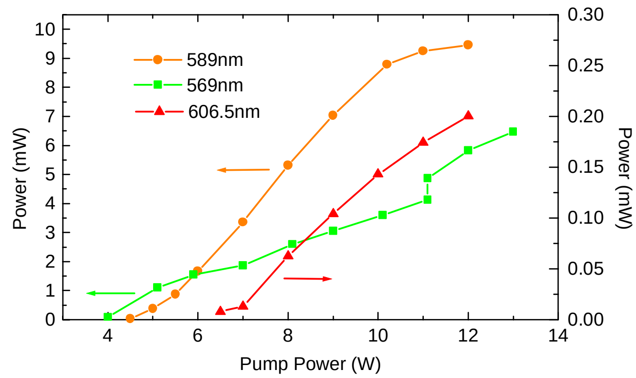

Fig. 3. The output power at 569nm, 589nm, and 606.5nm as a function of the pump power.

In the experiments the laser system was designed for 1178nm only, laser at 1250.5nm was determined by the Raman gain spectrum. Due to the broad Raman gain spectrum there is much flexibility in the laser wavelength in fact. One can choose the laser wavelength using corresponding FBG. In addition, in this study generation of multiple visible lasers is achieved by obtaining the phase matching condition for individual wavelength separately. Simultaneously generation of multiple visible lasers is possible by adopting aperiodically poled nonlinear crystals [7].

4. Summary

In summary, we have demonstrated multiple cw visible laser generation at wavelength ranging from 550nm to 625nm by the intracavity frequency sum mixing of a cascading Raman fiber laser in a type-I noncritically phase matched LBO crystal. The phase matching condition for the individual wavelength was realized by tuning the temperature of LBO crystal. The scheme has potential in simultaneous generation of multiple visible lasers, fiber based yellow-orange laser sources for laser guided star adaptive optics, and compact fiber based RGB laser sources for laser display by combination of other technology such as aperiodically poled nonlinear crystals.

Acknowledgments

This work is supported by the 21st Century COE program of Ministry of Education, Science and Culture of Japan. Yan Feng's webpage: http://geocities.com/yanfeng