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Generation of multiple laser lines by sum-frequency mixing of continuous-wave Raman emissions from a dispersion-compensated optical cavity

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ABSTRACT

Three color continuous-wave (CW) laser emissions with constant frequency separation are generated in the near-infrared (NIR) region using a dispersion-compensated optical cavity filled with hydrogen gas. By focusing these laser emissions into second-harmonic generation (SHG) crystals, multiple second harmonic signals and sum-frequency signals are generated in the near-ultraviolet (NUV) with a constant frequency spacing. Up to five colors of these NUV CW laser emissions can be generated simultaneously by using SHG crystals with different orientations. The interference between the second-harmonic signal of one NIR laser emission and the sum-frequency signal of the other two NIR emissions was observed experimentally, indicating mutual phase coherence among the NIR laser emissions. The phase coherence allows the synthesis of a train of ultrashort pulses with a THz repetition rate in both the NUV and the NIR by using the CW emission lines.

1. Introduction

Stimulated Raman scattering (SRS) and four-wave mixing (FWM) have been widely studied for the generation of trains of ultrashort pulses with THz-level repetition rates [1,2]. The generation of extremely short optical pulses with a repetition rate of approximately 100 THz has been experimentally demonstrated using a two-color nanosecond pump laser [1]. The pulse train generated in this way was formed within a nanosecond envelope, and it is difficult to use this scheme to generate a train of pulses without discontinuity. However, by using a continuous wave (CW) laser as a pump source, it is possible to generate trains of highly repetitive ultrashort pulses without such discontinuities [2]. Because the ultrashort pulse train generated in this manner consists of CW laser beams with narrow line widths, applications such as ultrahigh-speed communications and optical clocks are expected [3,4]. However, the peak power of a CW laser is too low to induce SRS or FWM. Use of an optical cavity with a Raman medium is one potential solution that would enhance the peak power of the laser beam and enable the generation of both SRS [5] and FWM [6]. The rotational Stokes and anti-Stokes emissions that are generated through SRS and FWM in a hydrogen-filled optical cavity are separated in frequency from the fundamental laser emission (i.e., the pump laser) by the rotational Raman shift for ortho-hydrogen of 587 cm^{-1}. By Fourier synthesis of the three emission lines, which consist of the Stokes, anti-Stokes, and fundamental emissions, it is possible in principle to synthesize a train of ultrashort pulses with a repetition rate of 17.6 THz [2,7]. Yavuz and coworkers reported the generation of Raman emissions [8,9]. In their work, a CW laser beam was focused into an optical cavity that was filled with hydrogen to prepare hydrogen molecules in a highly coherent state. The Raman emissions were then generated by passing a second laser beam through this cavity [9]. In general, the anti-Stokes emission has very low intensity when compared with that of the Stokes emission. To generate anti-Stokes emission with high efficiency, the anti-Stokes emission must be resonant in the cavity. To provide this resonance, it is necessary to control the frequency spacing of the longitudinal modes of the cavity. A dispersion-compensated high-finesse cavity was used for spacing control to enable generation of the anti-Stokes emission with high efficiency [6]. The three CW laser emissions that emerge from the cavity, i.e., the fundamental, first Stokes, and first anti-Stokes emissions, are expected to show mutual phase coherence, although this property has not been characterized to date. This phase coherence plays a crucial role in the long-term waveform stability of the ultrashort pulse trains that are synthesized using these emission lines.

In this research, the frequencies of the multicolor CW laser

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lines generated using the dispersion-compensated cavity are converted to NUV frequencies to investigate the mutual phase coherence among the three laser lines. The phase coherence relies on the interference between the second harmonic generation (SHG) process of the fundamental emission and the sum-frequency generation (SFG) processes of the Stokes and anti-Stokes emissions [8]. The possibility of a multicolor CW laser system in the NUV region is also investigated. The SHG and SFG processes produce up to five CW laser emission colors in the NUV region, which are separated in frequency by the Raman shift. The scheme uses thick SHG crystals for simultaneous generation of these emissions, and would produce an NUV frequency comb consisting of five CW laser lines with a constant frequency spacing.

2. Theoretical background

The first anti-Stokes emission that is generated by four-wave Raman mixing in an optical cavity [6] has a phase of $\varphi_{AS,0} = 2\varphi_{P,0} - \varphi_{S,0} + \frac{\pi}{2}$ [10], where $\varphi_{P,0}$ and $\varphi_{S,0}$ are the phases of the pump and first Stokes emissions, respectively. The three emissions pass through the hydrogen gas, the output window of the cavity, and the air outside the cavity. Assuming that the emissions also pass through an additional glass plate with thickness L that is placed behind the cavity, the resulting phases of each emission are:

$$\varphi_p(t, L) = \varphi_{P,0} - \omega_P t + R_P L + \Delta\varphi_P,$$

$$\varphi_S(t, L) = \varphi_{S,0} - \omega_S t + R_S L + \Delta\varphi_S,$$

$$\varphi_{AS}(t, L) = \varphi_{AS,0} - \omega_{AS} t + R_S L + \Delta\varphi_{AS},$$

where ϕ_i, ω_i, and R_i are the phase, angular frequency, and rate of phase change of each emission due to propagation through the glass plate, respectively. The parameter $\Delta\phi_i$ is the accumulated phase change of each emission during propagation through the hydrogen gas, the output window, and air. By focusing these emissions into a birefringent crystal, second harmonic (SH) signals and sum-frequency (SF) signals are generated. Because the SH of the fundamental emission and the SF signal of the Stokes and anti-Stokes emissions are generated at the same frequency, these signals interfere with each other provided that there is mutual phase coherence among the fundamental, Stokes, and anti-Stokes emissions. The intensity of the generated signal varies with the relative phase change among the three light waves. For the condition where $\varphi_P = \varphi_S = \varphi_{AS}$ (i.e., phase locking), L can be expressed as follows:

$$L = L_{(n)} = \frac{1}{2R_P - R_S - R_{AS}}\left(\frac{\pi}{2} - 2\Delta\varphi_P + \Delta\varphi_S + \Delta\varphi_{AS} - 2\pi n\right),$$

where n is an integer. The phase locking condition appears repeatedly, with a period ΔL:

$$\Delta L = L_{(n+1)} - L_{(n)} = \frac{-2\pi}{2R_F - R_S - R_{AS}}$$

In the case of a glass plate made from BK7 glass, the period ΔL is calculated to be 12.8 mm for a fundamental emission at 852 nm and the rotational Stokes and anti-Stokes emissions of molecular hydrogen. This means that by changing the thickness of the glass, the signal intensity can be varied periodically with a period of 12.8 mm.

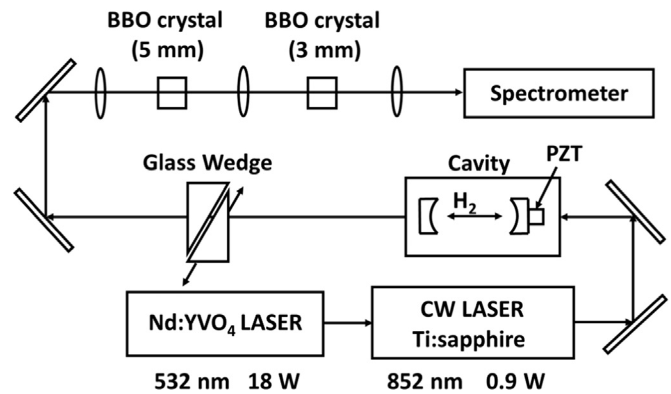

Fig. 1. Experimental setup.

3. Experimental

The experimental setup is as shown in Fig. 1. Similar to previous research in this area, the CW laser, emitting at a wavelength of 852 nm (Ti:sapphire laser, 1.0 W, Coherent MBR110, Santa Clara, California, USA), was focused into a dispersion-compensated optical cavity that was filled with hydrogen gas at 953 kPa [4]. The Raman emissions (anti-Stokes wavelength: 812 nm; Stokes wavelength: 897 nm) were generated simultaneously. After the output beam, consisting of the three wavelength components, passed through a pair of wedges made from BK7, the beam was focused into a 5 mm-thick beta barium borate (BBO) crystal by a convex lens with a focal length of 120 mm. After being collimated (f=100 mm), the output beam from the BBO crystal was focused into another 3 mm-thick BBO crystal by a lens with a focal length of 70 mm. Then, the spectra of the SH and SF emissions generated in the BBO crystals were measured by focusing these signals into a multi-channel spectrometer (Ocean Optics, HR4000) using a plano-convex lens (f=80 mm). The focal lengths of the lenses used to focus the beams into the crystals were selected to provide high SH and SF signal generation efficiency by matching the confocal distances and thicknesses of the BBO crystals.

4. Results and discussion

The spectrum of the beam that was output from the optical cavity is shown in Fig. 2. The output beam consisted of the

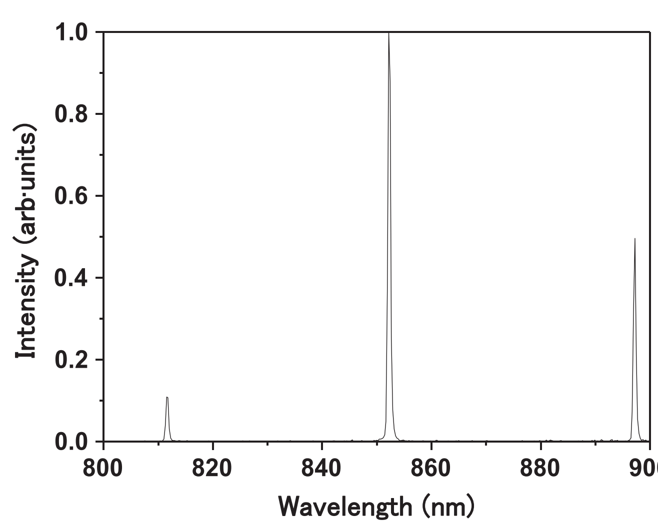

Fig. 2. Spectrum of output beam from high-finesse cavity filled with hydrogen gas at 953 kPa.