Experimental and Numerical Analysis of a Two-Order Cascaded Raman Fibre Laser *

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A two-order cascaded Raman fibre laser based on GeO_2-SiO_2 fibre and fibre Bragg gratings is fabricated. Output power 309 mW of the second Stokes light around 1176.2 nm is obtained with a slope efficiency of 45.3%. The experimental results agree well with the simulation results obtained by using the double-pass model.

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Stimulated Raman scattering (SRS) in optical fibres represents a very interesting method to amplify optical signals and to generate new laser wavelength.[1,2] With applications of high-power pump laser and low-loss high-reflective fibre Bragg gratings (FBGs), the cascaded fibre Raman cavities can be easily formed by FBG mirrors. In the cavities, five or six Stokes lights can be simultaneously resonated by SRS, and the pump power can be very efficiently converted to the highest-order Stokes lights. Such a high-power cascaded Raman fibre laser (RFL) consisted of the cavities is very helpful as a pump source for Raman fibre amplifiers and other fibre lasers.

The earlier papers[3,4] presenting numerical solutions of the laser equations were considering only forward stimulated Raman scattering and the pump light contributions. They are applicable to describe a unidirectional ring resonator, but cannot be used for the cascaded fibre Raman cavities. Recently, a novel double-pass model[5,6] has been presented. In the model, all interactions between forward and backward travelling lights are taken into account. Thus, the model can be suitable for analysis of nth-order cascaded Raman fibre laser performance.

In this Letter, a two-order cascaded Raman fibre laser based on a single-mode germanosilicate (GeO_2-SiO_2) fibre has been reported. The numerical analyses are given by using double-pass model, where a comparison is made between the results of the experiment and that of the simulation.

The experimental set-up is shown in Fig. 1. The pump source is a Yb-doped double-clad fibre laser (DCFL), pumped by a laser diode with emission wavelength of 976 nm, with single-mode fibre output at 1060 nm. The two cascaded fibre Raman cavities consist of 2.2 km of GeO_2-SiO_2 fibre and two pairs of FBG mirrors written on the Flexcor-1060 fibre. The core diameter of the GeO_2-SiO_2 fibre is 5.5 μm, cut-off wavelength of 0.95 μm. The optical losses at 1060, 1115, and 1176 nm are 1.0, 0.85, and 0.7 dB/km, respectively. The measured values of the ratio between the Raman gain coefficient and the effective core area ($g_R/A_{\rm eff}$) are 1.78 and 1.5 dB·km^{-1}W^{-1}, respectively. The reflectivities of FBG2 and FBG4 mirrors at 1115 nm both are 99%, while the reflectivities of FBG1 and FBG5 mirrors at 1176 nm are 99% and 15%, respectively. The reflectivity of an additional FBG3 mirror used for yielding a double-pass pumping scheme is 99% at 1060 nm.

The output powers of the residual pump (RP), the first Stokes (S_1) and second Stokes (S_2) lights are measured for the change of the input pump power (IPP). The output spectra of the RFL at different input pump powers of 0.21 W, 0.30 W, 0.42 W, and 1.05 W, respectively, which include the RP, the S_1 and the S_2 lights, are observed as shown in Fig. 2.

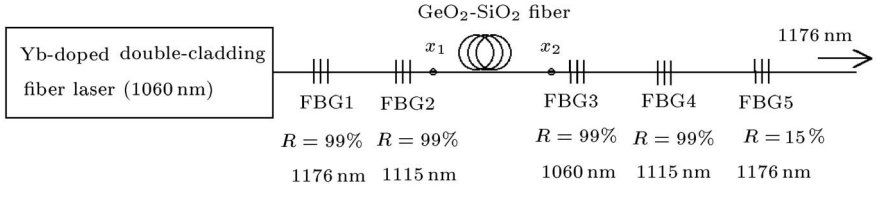


Fig. 1. Experimental set-up of two-order cascaded Raman fibre laser.

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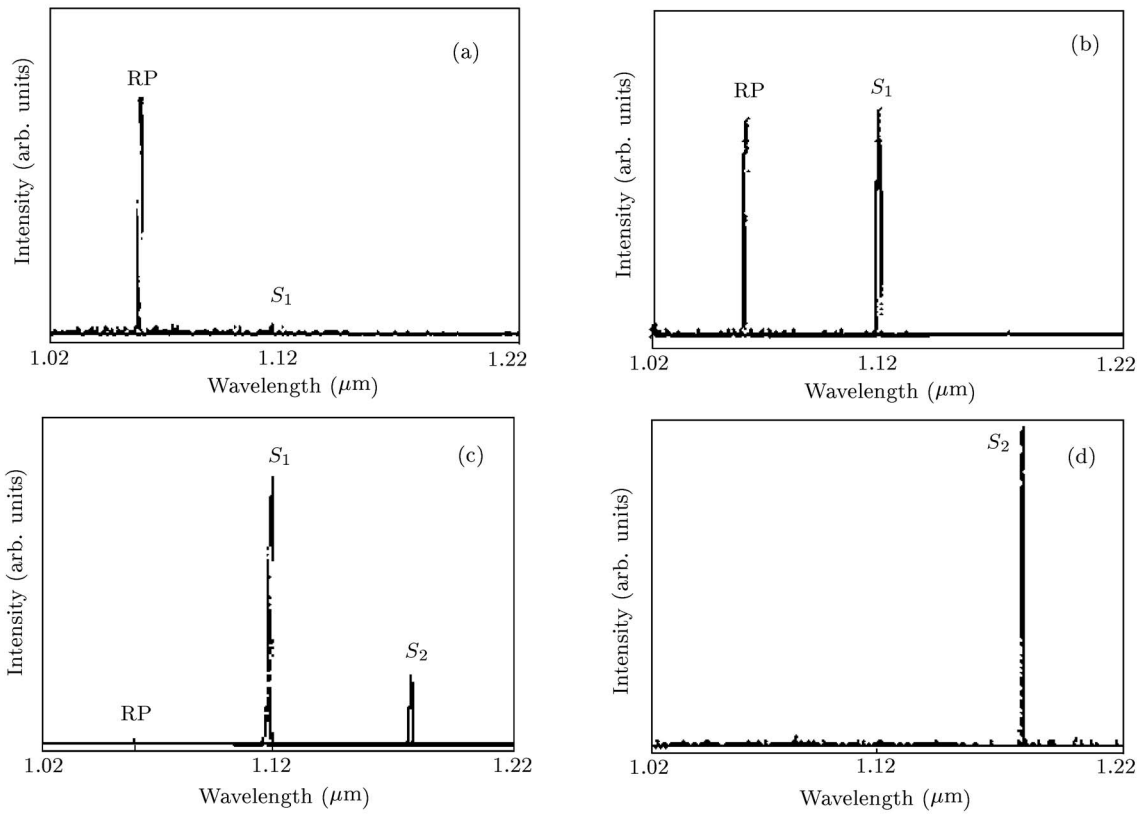


Fig. 2. Output spectra of the two-order cascaded RFL at different input pump powers: (a) 0.21 W, (b) 0.3 W, (c) 0.42 W, (d) 1.05 W.

Figure 2(a) shows that the S_1 light at 1115 nm begins to generate when the IPP is increased to 0.21 W, and only the spectrum of the RP light is observed clearly. When the IPP is increased from 0.21 W to 0.3 W, the RP power decreases because the IPP is used in generation of the S_1 light as shown in Fig. 2(b). When the IPP is above 0.4 W, the RP power decreases slowly and the S_1 power is still increasing with the IPP. At the same time, the S_2 light at 1176.2 nm has been generated as shown in Fig. 2(c). The decrease of the RP power and increasing the S_1 power are believed because amount of the IPP are still converted to the S_1 power. Figure 2(d) shows that when the IPP is increased to 1.05 W, the RPP and the S_1 power decrease quickly with the IPP and the S_2 power increases quickly up to 309 mW. The decrease of the S_1 power is ascribed to the power transfer from the S_1 to the S_2 light.

The output power of the S_2 light versus the IPP is shown in Fig. 3. The slope efficiency of the S_2 light is about 45.3%. The total cavity loss at 1060 nm is 3 dB determined by measuring the RP power before the S_1 and S_2 lights are generated, including the 2.2 dB loss for the GeO_2-SiO_2 fibre, the excess loss due to insertion losses for the five FBG mirrors (0.1 dB for each) and splicing losses for the two points, X_1 and X_2 (0.15 dB for each). A higher output power can be expected when the total cavity loss is reduced further.

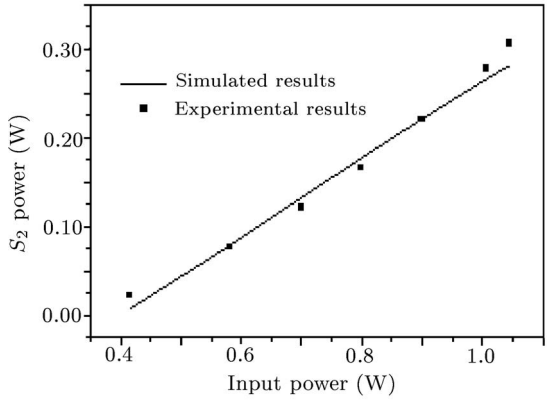


Fig. 3. Measured and simulated S_2 output power versus input pump power.

In accordance with the experiment, the backward pump lights must be taken into account. Thus, the two-order cascaded RFL can be modelled using the nonlinear coupled differential equations as follows,

$$\frac{\mathrm{d}P_p^{F/B}}{\mathrm{d}z} = \mp \frac{g_1}{A_1}\frac{\nu_p}{\nu_1}P_p^{F/B}(P_{s1}^F + P_{s1}^B) \mp \alpha_p P_p^{F/B},$$

$$\frac{\mathrm{d}P_{s1}^{F/B}}{\mathrm{d}z} = \pm \frac{g_1}{A_1}(P_p^F + P_p^B)P_{s1}^{F/B}$$

$$\mp \frac{g_2}{A_2}\frac{\nu_1}{\nu_2}P_{s1}^{F/B}(P_{s2}^{F}+P_{s2}^{B}) \mp \alpha_{s1}P_{s1}^{F/B},$$
$$\frac{\mathrm{d}P_{s2}^{F/B}}{\mathrm{d}z} = \pm \frac{g_2}{A_2}(P_{s1}^{F}+P_{s1}^{B})P_{s2}^{F/B} \mp \alpha_{s2}P_{s2}^{F/B}, \quad (1)$$

where z is the coordinate along the fibre, P_p, P_{s1} and P_{s2} represent the pump, S_1 and S_2 powers (F denotes forward and B for backward propagating), ν_p, ν_{s1} and ν_{s2} represent their frequencies. The parameter g_n $(n = 1, 2)$ is the Raman gain coefficient at 1115 nm and 1176 nm, α_p, α_{s1}, and α_{s2} are the linear attenuation coefficients at the pump and the Stokes wavelengths, respectively; A_n $(n = 1, 2)$ is the effective core area.

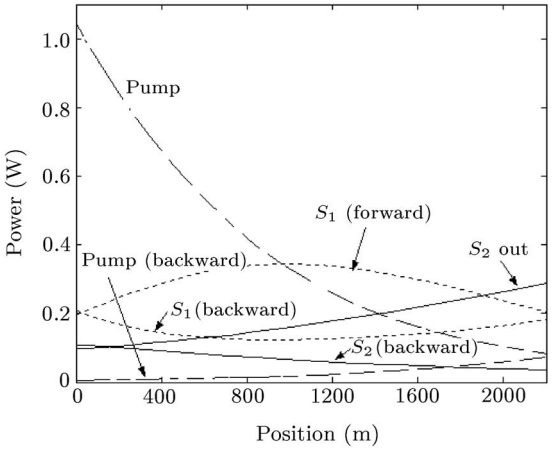


Fig. 4. Evolution of forward/backward of the pump, S_1 and S_2 powers along the fibre with input pump power of 1.05 W.

The boundary conditions at $z = 0$ and $z = L$ are given as follows:

$$\begin{aligned} P_p(0) &= P_{IN}, & P_p^B(L) &= R_3 P_p^F(L), \\ P_{s1}^F(0) &= R_1 P_{s1}^B(0), & P_{s1}^B(L) &= R_4 P_{s1}^F(L), \\ P_{s2}^F(0) &= R_2 P_{s2}^B(0), & P_{s2}^B(L) &= R_5 P_{s2}^F(L), \end{aligned} \quad (2)$$

where R_k are the reflectivities of the FBG mirrors. The numerical integration of Eq. (1), with the boundary conditions given by Eqs. (2), is performed using the shooting and the finite-difference method.

By using the measured values of the cavity parameters, we calculate the output power of the S_2 light versus IPP as shown by the full lines in Fig. 3. The threshold power derived from the simulation is 0.36 W and the slope efficiency is about 43.6%, both values being very close to the experimental ones. The evolution of forward and backward of the pump, S_1 and S_2 powers along the fibre are also calculated and shown in Fig. 4 when the IPP is 1.05 W.

In conclusion, a two-order cascaded Raman fibre laser, pumped at 1060 nm, using two Stokes shift to produce an output radiation at 1176.2 nm has been demonstrated for the first time. We have presented a test of the double-pass model that describes the two cascaded fibre Raman cavities formed by FBG mirrors. The output performance for the RFL has been measured and calculated. The agreement between theory and experiment is very good.

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