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Continuous-wave pumped, all-fiber optical parametric oscillator assisted by stimulated Raman scattering

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ABSTRACT

A continuous-wave pumped, all-fiber optical parametric oscillator (OPO) around 1523 nm based on the mixing interaction of parametric process and stimulated Raman scattering (SRS) effects are investigated in this paper. We study and give the detailed analysis of the generation and output characteristics of all-fiber OPO with the influence of the SRS effects. Experimental results show that there exists the saturation output effect for this kind of OPO due to the coexistence of first order SRS effect, second order SRS and the optical parametric oscillation. The maximal output power of OPO is about 100 mW as the pump power reaches 1.4 W. Furthermore, a depolarized L-band super-continuum light source from 1570 nm to 1640 nm based on the combined interaction of parametric process and SRS effects can also be obtained.

1. Introduction

There has been increasing demand on high-power continuous wave (CW) fiber sources due to their potential applications in telecommunications, spectroscopy and medicine [1]. Optical parametric oscillator (OPO) is widely recognized as an important application for the development of coherent light sources at the wavelengths unavailable for conventional lasers [2]. Generally, OPO is constructed utilizing nonlinear crystals and bulk optics elements, which requires careful alignment in order to achieve optimal operation [3]. Optical fiber is an ideal medium to generate nonlinear optical effects due to its light confinement and low losses, and fiber OPO has also been reported previously [4,5]. However, due to the relatively low nonlinear coefficient of optical fibers compared with nonlinear crystal or bulk optics elements, either pulsed pumps or high power CW Raman fiber laser (RFL) is necessary requirement for OPO. Early theoretical and experimental studies revealed that Raman assisted four-wave mixing (FWM) typically leads to improved conversion efficiency and parametric gain bandwidth of systems [6–10]. There are also theoretical and experimental investigations on the characteristics and features of OPO assisted by Raman effect in fiber [10]. However, there are few reports about the generation of OPO based on the mixing interactions of parametric process and SRS effects in fiber. Especially, the first order SRS of pump laser is also served as the media of the optical parametric oscillation. In this paper, the influence of SRS on the output characteristics of all-fiber OPO is investigated in detail. The maximal output power of OPO is about 100 mW as the pump power reaches 1.4 W. In addition, a depolarized L-band broadband source of 1570–1640 nm can also be obtained together with the generation of all-fiber OPO. We also studied the characteristics and generation process of this depolarized broadband source.

2. Experimental setup

The experimental setup for all-fiber OPO assisted by SRS is shown in Fig. 1a. It is a ring cavity comprising a Raman pump source, a broadband wavelength division multiplexer (WDM) coupler, 3 km highly nonlinear dispersion-shifted fiber (HNDSF), an optical isolator (ISO), a polarization controller (PC) and a broadband fiber power splitter. The Raman pump source is a CW RFL with the maximal output powers of 4 W at 1395 nm. The pump beam has a degree of polarization less than 5%. The broadband WDM coupler is used to couple the pump into the 3 km HNDSF and re-input the SRS generated in HNDSF back into the ring cavity. The splitter is used to extract approximately 10% of the oscillation light from the cavity. The nonlinear coefficient of the HNDSF is 12 W^{-1} km^{-1} and its zero dispersion wavelength (ZDW) is at 1570 nm, with a dispersion slope of 0.015 ps/nm^2 km, as shown in Fig. 1b. The insertion loss of 3 km HNDSF is about 1.6 dB. The optical ISO is used to ensure unidirectional oscillation of the cavity and the PC is used to adjust the polarization state of lights in the cavity in order to obtain the maximal output power of all-fiber OPO. WDM coupler and optical power splitter is specially designed and the insertion loss for them is very little. In addition, both of them have a broadband and flat transmission spectrum for signal port, which can cover from 1520 nm to 1620 nm. The transmission

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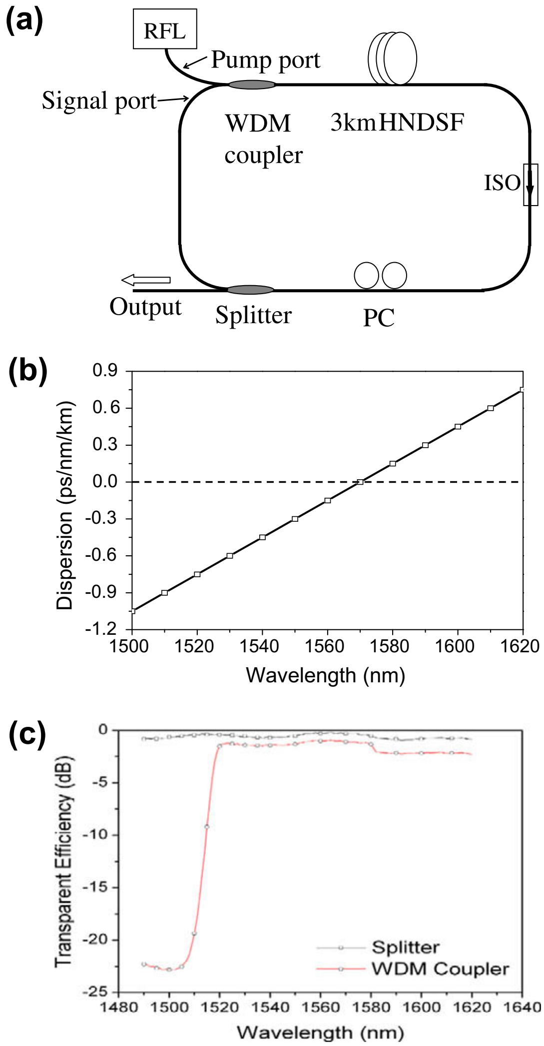

Fig. 1. (a) Experimental setup of OPO; (b) dispersion map of HNDSF; and (c) transmission spectra of components in the cavity.

spectra of the components used in cavity are shown in Fig. 1c, which shows that the signal port of the WDM coupler has a high transmission ratio as the wavelength is longer than 1520 nm, while the pump port has a high transmission ratio as the wavelength is shorter than 1520 nm.

3. Results of parametric amplification

Since the RFL is made based on the cascaded SRS, new lasing components appear due to FWM among different orders SRS in the laser cavity [1]. Fig. 2a shows the special output spectrum of the RFL used in this experiment. In addition to the main peak at 1395 nm, there is also a little peak component around 1445 nm. The power of this peak component at 1445 nm is about 30 dB lower than that of the main peak at 1395 nm. In Fig. 2a, we have denoted the 1395 nm and 1445 nm lines as λ_{RFL1} and λ_{RFL2}, respectively. The one-pass spectrum of the RFL beam through the HNDSF, which is measured before the ring cavity is formed, is shown in Fig. 2b. Other than the original peak components inherent to the RFL, there appear two new peak components around 1483 nm and 1523 nm, respectively. The peak component around 1483 nm is generated due to the first order SRS (FOSRS) effect of the lasing component at 1395 nm, and its 20 dB down bandwidth is about 10 nm, while the peak component at 1523 nm is formed through the four-wave

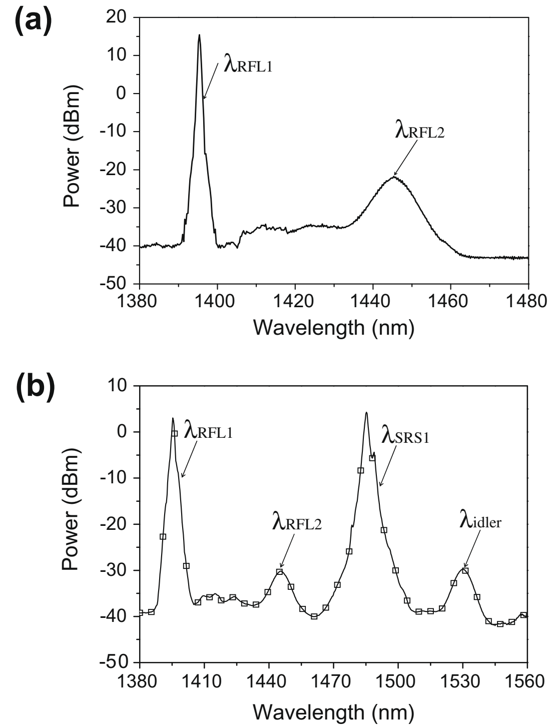

Fig. 2. (a) Output spectrum of RFL; and (b) output spectrum after RFL passing HNDSF for single time.

parametric process between the λ_{RFL2} and the strong 1483 nm spectral components. We have denoted the peak components at 1483 nm and 1523 nm as λ_{SRS1} and λ_{idler}, respectively. It can be found that the generated new wavelengths agree well with typical parametric four-wave mixing process, which can be represented by Eq. (1), where ω_{SRS1}, ω_{RFL2} and ω_{idler} are the angular frequencies of λ_{SRS1}, λ_{RFL2} and λ_{idler}, respectively.

$$2\omega_{SRS1} = \omega_{RFL2} + \omega_{idler} \tag{1}$$

4. Results and discussions in OPO process

We have obtained a new peak component at 1523 nm through the above parametric process. In order to improve its output power, we then construct a resonant cavity as shown in Fig. 1a to utilize this parametric gain for more times. According to the transmission bandwidth (1520 nm) at the signal port of broadband WDM coupler used, only the peak component at 1523 nm has the least attenuation and can oscillate in the cavity, while the other peak components at wavelengths of λ_{SRS1}, λ_{RFL1} and λ_{RFL2} will be blocked by the rejection band of WDM coupler. We find that under strong pumping, laser oscillation of the peak component at 1523 nm can indeed be obtained, and therefore, a SRS assisted all-fiber OPO is demonstrated. For clarity, typical spectra of this all-fiber OPO at three different RFL output power levels are shown in Fig. 3a. The operation of this all-fiber OPO exhibits the following characteristics: as the pump power is more than 1.0 W, the output power of the all-fiber OPO starts to increase with the RFL power, until it reaches the maximal value, it then decreases with the further increase of the RFL power. Fig. 3b shows the all-fiber OPO output power measured by selecting OPO wavelength using an optical filter. The 20 dB bandwidth of this optical bandpass filter is about 10 nm. Fig. 3b shows that the maximal all-fiber OPO output power occurs as the RFL pump power reaches 1.4 W, with a value about 100mW. The SRS assisted all-fiber OPO shows clear difference to

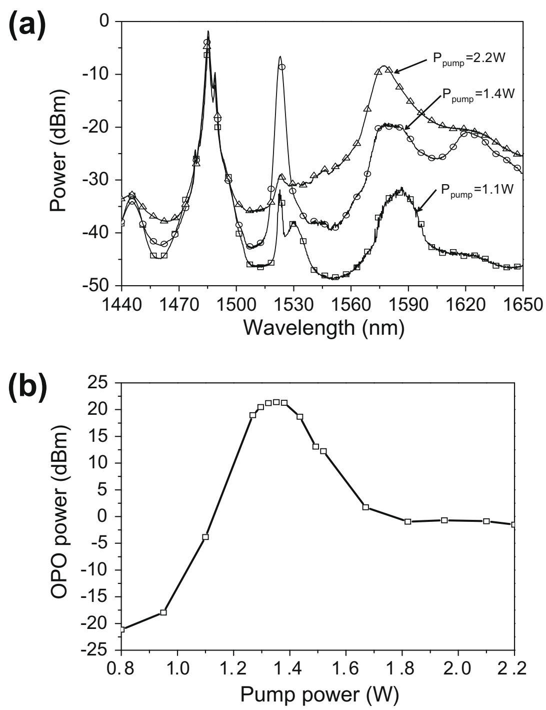

Fig. 3. (a) Output spectra of the fiber OPO under different pump powers; and (b) output power of OPO signal versus pump power.

the conventional OPO systems in that the latter's output power becomes to saturate when we further increase the output power of RFL [2–4]. We find that this property of the SRS assisted all-fiber OPO is caused by the coexistence of a higher order SRS process together with parametric process. In addition to the parametric process, the FOSRS also transfer energy to the second order SRS (SOSRS), and the two processes compete with each other. In our system, the obvious FOSRS appears when the RFL output power reaches 700 mW, and it increases further until the appearance of the OPO component. Then with the further increase of pump power, the pump energy transferred to the parametric oscillation process becomes dominant. The output power of all-fiber OPO increases continuously until the RFL power reaches 1.4 W, where the Raman lasing at the SOSRS starts, and consequently the energy transferred to the SOSRS becomes dominant. As a result, the OPO component begins to decrease, while the SOSRS increases continuously.

As shown in Fig. 3a, before the SOSRS starts to lasing, an L-band broadband source appears from 1570 nm to 1640 nm. The single peak component at 1580 nm corresponds to the SOSRS of RFL and its 3 dB bandwidth is about 20 nm. As the RFL power increases, its 3 dB bandwidth increases. In particular, the broadening at the bottom part of this peak component is more significant than that at the top. During the process of the appearance and increasing of OPO component, a new peak around 1620 nm due to the SRS of the OPO signal appears. As a result, 10 dB bandwidth of the broadband source can be extended more than 80 nm with ripple less than 5 dB when the RFL power is 1.4 W. The output power of broadband source filtered out by another WDM at the output port of the splitter is more than 50 mW. With the pump power increasing further, the peak at 1620 nm decreases gradually associated with the decrease of the OPO strength. It is observed that the bandwidth at top of the SOSRS spectrum becomes further narrowed with the increase of the output power of RFL since the SOSRS reached the lasing threshold and start to lasing, while the bandwidth at the bottom of the SOSRS spectrum broadened at the same time. The broadening of the spectrum can be attributed to the FWM process between the SOSRS Stokes waves and the broadband Raman scattering background due to SOSRS spectrum generated near the ZDW of HNDSF [11].

Because OPO signal or broadband source is usually used to investigate the spectral characteristics of devices, it is important to avoid the influence of the polarization state on experimental results. Therefore, having a polarization insensitive OPO and broadband source is important. In our experiment, the polarization state (PS) of the output spectra is investigated. No variation in either the output power or spectral shape of the OPO signal and broadband source is observed as the PC is rotated. This polarization insensitivity of the OPO and broadband source can be attributed to the very low degree of polarization of the RFL [11].

5. Conclusions

In this paper, a SRS assisted polarization insensitive all-fiber OPO is developed and investigated. The maximal output power of OPO is about 100 mW as the pump power reaches 1.4 W. A depolarized L-band broadband source ranging from 1570 nm to 1640 nm with high output power and flat spectrum is generated due to the combined action of the second order SRS and parametric process.

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