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Waveband-switchable multiwavelength mixed-cascaded phosphosilicate raman fiber lasers

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ABSTRACT

In this paper, the mixed-cascaded Raman scattering has been developed to investigate multiwavelength phosphosilicate Raman fiber lasers (MRFLs). With a tunable Yb^{3+}-doped double-clad fiber laser (YDCFL) as the Raman pump source, we propose a compact and waveband-switchable (from the *O*- to *U*-band) MRFL using two- or three-mixed-cascaded Raman scattering of both SiO_2/GeO_2 and P_2O_5 in a P-doped fiber. We also confirm experimentally the feasibility of the proposed mixed-cascaded MRFL. When a 1064 nm YDCFL was used to pump a spool of 1-km P-doped fiber, the compact linear-cavity MRFLs in the *O*- and *L*-band operation were obtained, respectively, based on the two- and three-mixed cascaded Raman scattering. Up to 16-wavelength stable oscillation around 1320 nm has been observed with a spacing of 0.40 nm and an extinction ratio >30 dB. 12 lasing lines around 1601 nm have also been achieved with a spacing of 0.58 nm. The multiwavelength output powers as high as 108 and 138 mW were obtained in the *O*- and *L*-band operations, respectively. The wavelength spacing of the MRFLs is flexibly adjustable, and the peak wavelength of each lasing line is continuously tunable over the wavelength spacing. In addition, the important characteristics of the mixed-cascaded MRFLs, including the linewidth broadening, the signal-to-noise ratio and the conversion efficiency, are discussed.

1. Introduction

Multiwavelength fiber lasers (MFLs) have attracted extensive attention in recent years, owing to their great potential applications in fiber-optic sensors [1–4], optical instrument testing, microwave photonic generation [5,6] and optical fiber communication systems [7,8], etc. Currently, several gain mechanisms have been employed to realize MFLs, such as erbium-doped fiber (EDF) [9–16], semiconductor optical amplifier (SOA) [17–19], stimulated Raman scattering (SRS) [20–27], optical parametric process [28] and hybrid gain media [29,30]. However, because of the homogeneous broadening of erbium ions, it is relatively difficult to realize the stable multiwavelength lasing in an EDF at room temperature unless an additional technique [10,16] is used to suppress the mode competition. Moreover, the gain bandwidth of EDF also limits the multiwavelength operation range in the *C*- or *L*-band. Although the bother of homogeneous broadening can be avoided using an SOA as the gain medium, most SOA-based MFLs provide very low output power, which imposes some constraints in their practical applications. In contrast, if one uses the SRS in a single-mode fiber, high-power multiwavelength lasing can be realized in arbitrary wavebands by properly selecting Raman pump source, and there would be no problems of the EDF- and SOA-based MFLs as mentioned in above.

Using some different Raman pump techniques, multiwavelength Raman fiber lasers (MRFLs) have been widely investigated over the past years [20–27]. By combining an array of semiconductor laser diodes (LDs) as Raman pump sources, Han et al. have successfully achieved high-performance *C*-band MRFLs with different kinds of fiber Bragg gratings (FBGs) as the comb-like filters [1,2,23,24]. When three LDs (1430, 1440 and 1467 nm) were used to pump a section of Raman gain fiber, Chen et al. [29] have also presented the spacing-tunable multiwavelength lasing using an optical variable delay line. However, by combining several LDs to obtain high-power Raman pump source, the pump system becomes complex and the system cost is considerably increased. Alternatively, it is well-developed to use a high-power Yb^{3+}-doped double-clad fiber laser (YDCFL) as the compact and high-performance Raman pump. By utilizing a 1064 nm YDCFL as Raman pump source and cascaded long-period fiber gratings as comb-like filter, Han et al. [22] have reported an *L*-band MRFL by

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seven-order Raman shifts of SiO_2/GeO_2. When a 10 W/1064 nm YDCFL is used to pump three different kinds of Raman gain fibers, Kim et al. [25] have successfully presented *S*- and *C*-band MRFLs with a polarization-maintaining fiber (PMF) Sagnac loop mirror as the comb-like filter. It should be noted that all of above-mentioned MRFLs use the SRS of SiO_2/GeO_2 in germanosilicate fiber as the gain mechanism due to its broad Raman bandwidth in favor of multiwavelength generation. However, since the Raman frequency-shift of SiO_2/GeO_2 in fiber is relatively small (~440 cm^{-1} only), several-order Raman cascaded cavities are generally required to obtain the desired lasing wavelength. For example, seven-cascaded Raman cavities were used to obtain the *C*-band multiwavelength Raman lasing from the pump wavelength of 1064 nm in Ref. [25]. So many Raman cascaded cavities result in the complexity and low efficiency of MRFL. Therefore, it is very important to reduce the Raman cascaded orders and simplify the laser system. A feasible solution is to use the larger Raman-shift (~1330 cm^{-1}) of P_2O_5 in P-doped fiber, instead of the smaller Raman-shift of SiO_2/GeO_2. Unfortunately, the SRS gain bandwidth of P_2O_5 is very narrow to the disadvantage of multiwavelength generation.

To solve the difficulty of multiwavelength Raman lasing in P-doped fiber, Luo et al. [26] recently proposed a new Raman gain mechanism (i.e. mixed-cascaded phosphor-silicate Raman scattering) which simultaneously uses the advantages of both the large Raman-shift of P_2O_5 and the broadband Raman gain of SiO_2/GeO_2 in a P-doped fiber. They have reported in brief an *O*-band multiwavelength mixed-cascaded phosphosilicate Raman fiber laser [26]. In this paper, using two- or three-mixed-cascaded Raman scattering, we comprehensively investigate the compact, waveband-switchable multiwavelength Raman fiber lasers. With a tunable YDCFL as Raman pump source, we propose a flexibly switchable *O*-, *E*-, *S*-, *C*-, *L*-, *U*-band multiwavelength mixed-cascaded phosphosilicate Raman fiber laser by tuning the Raman pump wavelength. The proposed MRFL needs only two- or three-cascaded Raman cavities, and hence significantly simplifies the laser system in comparison with a germanosilicate MRFL. When a 1064 nm YDCFL is used to pump a 1-km P-doped fiber, we demonstrate experimentally the *O*- and *L*-band MRFLs using the two- and three-mixed-cascaded Raman scattering, respectively. Up to 16 lasing lines in the *O*-band and 12 lasing lines in the *L*-band have been observed with a wavelength spacing of 0.44 and 0.58 nm, respectively. The multiwavelength output power in the *O*- and *L*-band is as high as 108 mW and 138 mW, respectively. The wavelength spacing is adjustable, and the peak wavelength of each lasing line is tunable over the wavelength spacing.

2. Proposal of waveband-switchable multiwavelength mixed-cascaded phosphosilicate Raman fiber laser

It is well-known that in the Raman spectrum of P-doped fiber there are two frequency-shift peaks originating from the Raman scattering of SiO_2/GeO_2 and P_2O_5. For the P-doped fiber used in our experiments, the measured Raman scattering spectrum is shown in Fig. 1 [31]. The P-doped fiber was manufactured by the Fiber Optics Research Center of the Russian Academy of Science, with 13 mol% of phosphorous in fiber core, a refractive index difference of 0.011 and a cutoff wavelength of 1000 nm. For 1064, 1239, and 1484 nm wavelengths, the fiber loss coefficients are 1.84, 1.16, and 1.01 dB/km, respectively. From Fig. 1, there are two Raman frequency peaks at wave-number of 495 cm^{-1} ($\Delta\nu_1$) and 1327 cm^{-1} ($\Delta\nu_2$), respectively, assigned to Raman scattering of SiO_2/GeO_2 and P_2O_5. Their Raman gain coefficients (at 1060 nm) of the two peaks are 0.85×10^{-3} and 1.20×10^{-3} W^{-1} m^{-1}, respectively.

One can find from Fig. 1 that the Raman scattering of P_2O_5 and SiO_2/GeO_2 have their respective features: (1) P_2O_5 can keep a very large Raman frequency-shift of 1327 cm^{-1}, but has a narrower Raman-scattering bandwidth; (2) the Raman scattering of SiO_2/GeO_2 has an ultra-broad bandwidth from ~300 cm^{-1} to ~600 cm^{-1}, but its Raman frequency-shift is relatively small (only 495 cm^{-1}).

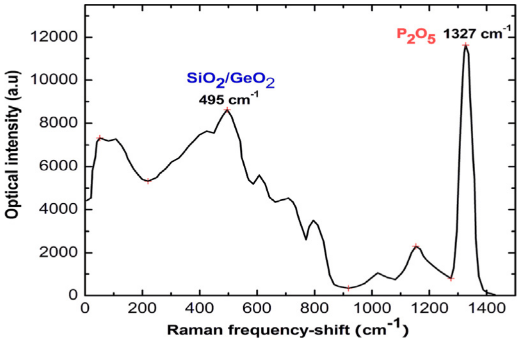

Fig. 1. The Raman scattering spectrum of the P-doped fiber [32].

Considering their applications in MRFLs, the SRS of P_2O_5 has a great potential to reduce the Raman cascaded orders, however, is unfavorable to realize multiwavelength lasing due to its narrow Raman bandwidth; on the other hand, the SRS of SiO_2/GeO_2 with ultra-broad gain bandwidth is very helpful to multiwavelength lasing, but the required Raman cascaded orders are usually too many for obtaining the expected wavelength due to its smaller Raman shift [25]. As a result, it is difficult or unsuitable to obtain a compact MRFL if using the SRS of P_2O_5 or SiO_2/GeO_2 only. In contrast, if one uses simultaneously their advantages of both P_2O_5 and SiO_2/GeO_2, namely, using the larger Raman shift of P_2O_5 and the broadband Raman gain of SiO_2/GeO_2, multiwavelength Raman lasing in any waveband can be realized in P-doped fiber by only few Raman-cascaded orders. To design an MRFL based on the proposed mixed-cascaded Raman scattering, the following rules should be required:

1) The last-order Raman shift for generating multi-wavelength oscillation must use the SRS of SiO_2/GeO_2 benefiting from its ultra-broad Raman gain as given in Fig. 1.
2) In order to minimize the Raman cascaded numbers for simplifying the MRFL system, the SRS of P_2O_5 should be used as many times as possible.

Complying with the two design rules, the proposed mixed-cascaded Raman process for realizing phosphosilicate MRFL can be described in principle by the following equations:

$$\frac{1}{\lambda_1} = \frac{1}{\lambda_p} - \Delta\nu_k \tag{1}$$

$$\vdots$$

$$\frac{1}{\lambda_{n+1}} = \frac{1}{\lambda_n} - \Delta\nu_k \tag{2}$$

$$\vdots$$

$$\frac{1}{\lambda_{N+1}^{\text{out}}} = \frac{1}{\lambda_N} - \Delta\nu_1 \tag{3}$$

Here λ_p is the Raman pump wavelength; $\lambda_n (n = 1, 2, \ldots)$ is the *n*th-order Stokes wave; $\lambda_{N+1}^{\text{out}} (N \geq n)$ is the central wavelength of the desired multiwavelength oscillation. $\Delta\nu_k (k = 1, 2)$ is the Raman frequency-shift of SiO_2/GeO_2 or P_2O_5 in P-doped fiber.