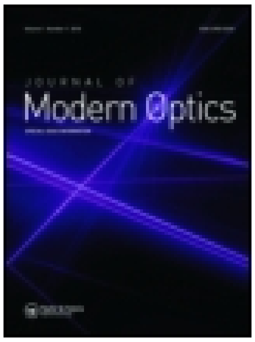

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Optimization of widely tuneable hybrid erbium-Raman-gain random fibre laser: theoretical investigation

Boli Su, Qingshan Luo, Lanying Zhao, Linlin Chu, Li Wang, Chunxia Liu & Xiuling He

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Institute of Disaster Prevention, Sanhe, People's Republic of China

ABSTRACT

In this study, we investigated the realization of maximum tuning range of a random fibre laser by adjusting the pump wavelength and power as well as changing the lengths of single-mode and erbium-doped fibres (SMF and EDF) to achieve hybrid erbium-Raman gain. With this hybrid gain, the widest tuning range was 90 nm (1524–1614 nm), optimal pump wavelength was 1489 nm, optimal SMF length was 10 km, and optimal EDF length was 15 m. The lasing power flatness is greatly improved with this optimization. Numerical results indicate that the optical conversion efficiency is as high as 71.1%, with a pump power of 2.7 W and an optical signal-to-noise ratio over 55 dB. Hence, this work effectively optimizes and inspires the exploration of and new schemes for broad wavelength tuneable and high-efficiency random fibre lasers.

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Tuneable random fibre laser; hybrid erbium-Raman gain; Rayleigh scattering; fibre Bragg grating

Introduction

The random distributed-feedback fibre laser (RFL) based on random Rayleigh feedback proposed by Turitsyn et al. [1] is a promising light source. Random fibre lasing has been hitherto demonstrated for photonic crystal fibres filled with scattering particles [2,3], optical fibres with random Rayleigh scattering feedback [4], and random fibre gratings [5,6]. RFLs with different features, such as ultra-wide wavelength tuneability [7,8], multiple wavelengths [9–11], narrow bandwidth [12–14], polarized outputs [15,16], high output power [17,18], and high-efficiency [19,20], have been demonstrated. RFLs have been considered in various applications, including remote sensing [21], distributed amplification [22] and imaging [23,24].

Due to the unique features such as the modeless property and structure simplicity, RFLs provide new platform to develop novel wavelength tuneable laser sources. Babin et al. made a first step to demonstrate a 1535–1560 nm tuneable random Raman fibre laser by inserting a tuneable filter into the lasing cavity [25]. Sarmani reported a 1550–1571 nm tuneable random laser, and they also discovered that the spectral broadening effect between the modeless spectra resembled the same process that happens in a typical fibre cavity with high reflectors at cavity end [26]. By employing the cascaded random Raman fibre lasers and using the wavelength tuneable ytterbium-doped fibre laser as the pump, ultra-wide tuneable RFL in 1–1.9 µm wavelength regions can be achieved [7,8,27]. However, the laser thresholds of Raman gain based tuneable RFLs are typically high. Moreover, to realize tuneable C band RFL pumped by tuneable ytterbium-doped fibre laser, up to 5th order cascaded Raman process is need, which requires the high-power pump source. RFLs based on the rare-earth doped gain could operate with much lower thresholds with good wavelength tunability. Tuneable RFL in 1 µm has been demonstrated with ytterbium (Yb) -doped fibre [28]. Erbium (Er)-doped RFL has also been realized with milliwatts threshold and can be tuneable in C band (1525–1565 nm) [29]. However, the demonstrated Er-doped RFL has a poor laser efficiency due to the loss induced in the long passive single mode fibre [29]. To realize the simultaneous low-threshold and high-efficiency, the hybrid Er-Raman gain has been used in RFL with the single 1455 nm pump [17], and the Er-Raman RFL provide a new way to realize high performance fibre laser in C band. Besides, the use of hybrid Er-Raman gain gives the possibility to further broaden the wavelength tuning range of RFL, by considering the combination of the gain bandwidth of Er-doped gain and Raman gain. Recently, Bian et al. experimentally presented a hybrid Er-Raman gain RFL with a forward pumping scheme and demonstrated a wide tuneable

CONTACT Boli Su sbl@cidp.edu.cn Institute of Disaster Prevention, No. 465, Xueyuan street, Yanjiao High-tech Zone, Sanhe, Hebei, 065201, People's Republic of China

range (1524.9–1602.7 nm) covering both the C and L bands [30], which is much broader than that of Raman gain [25] or Er-doped gain RFL [29]. However, to realize widely tuneable, high-efficiency hybrid Er-Raman gain RFL, both the pump wavelength and the fibre lengths need to be optimized, which has not been done in the previous works.

In the present work, we make a thorough study on the wide tuneability, high-efficiency hybrid erbium-Raman-gain RFL which based on backward pumping scheme. First, we numerically analyse the influence of pump wavelength on the tuneability with the pump power of 1.5 W. The simulated results show that the tuning range gradually increases with pump wavelength increases, when the pump wavelength is 1490 nm, the tuning range is up to 90 nm (1524–1614 nm). Second, by adjusting SMF length, EDF length, and pump power simultaneously, the lasing power flatness is greatly improved. Third, the influence of the pump power increase on the tuning range is investigated. Owing to the hybrid erbium-Raman gain, the 1600 nm random lasing with high OSNR and relatively low-threshold can be achieved. Furthermore, we calculate the discrete values of lasing power and optical conversion efficiencies, the optimal values of pump wavelength and SMF length are derived. The results show that by optimizing parameters proposes a widely tuneable hybrid erbium-Raman gain RFL with high-efficiency simultaneously.

Principle and numerical modelling

The proposed cavity design for generating tuneable hybrid Er-Raman gain random fibre laser is shown in Figure 1. A pump source is launched into 10-km-long SMF (Corning SMF 28e+) through WDM (insertion loss: 0.3 dB). An EDF (EDFC-980-HP, Nufern) is coupled to the SMF to provide both the Raman gain in the SMF and erbium-doped gain in the EDF. The lengths of the SMF and EDF are investigated to obtain maximum tuning range and optical conversion efficiency. A fibre Bragg grating (FBG) with a different central wavelength and reflection of ∼95% is spliced to the far end of the EDF. The generated random lasing is pumped by a backward-pumping scheme. The other port of the WDM system is the output of the laser.

Using a remote pump, amplified spontaneous emission (ASE) light of around 1523–1610 nm can be simulated in the EDF. The light reflected by the FBG will propagate backward into the SMF. The generated lasing experiences Raman gain and random distributed Rayleigh feedback in the SMF. By dynamically adjusting the pump wavelength, SMF length, EDF length, and pump power, the maximum Raman and erbium-doped gains can be combined so that the simulated laser has a wide tuning range of up to 90 nm.

To theoretically analyse the optimal pump wavelength, EDF's optional length, and optimal pump power of the RFL system, the power balance model was established. In the following Equations (1)–(4), the superscripts '+' and '−' correspond to the forward and backward waves, respectively, and subscript 'k' represents light waves with the k-th calculated wavelength. The calculated Stokes wavelength ranges from 1520 to 1600 nm in wavelength intervals of 0.2 nm; P_k represents the power, and ν_k represents the frequency of the light wave. Equations (1) and (2) are the Giles model for calculating the EDF gain. N_2 is the Er-ion population of the upper energy level, and N_t is the total Er-ion population of the ground state and upper energy level. $\Delta\nu_{ke}$ represents the noise bandwidth, ζ $(=3.87\times10^{15}\ \mathrm{m^{-1}s^{-1}})$ is the saturation parameter, and l_k $(=0.01\ \mathrm{dB/m})$ is the background loss. The values of the attenuation coefficient α_k^* and gain coefficient g_k^* are provided by Nufern (EDFC-980-HP). The Raman gain, Rayleigh backscattering, and fibre loss in the SMF are calculated using Equations (3) and (4); η in Equation (3) is a control index related to 'k' such that when $k = 0$, η is set to 1 and Equation (3) can be used to calculate the pump light; when $k \neq 0$, η is set to 0 and Equation (3) can be used to calculate the first-order Stokes light. Γ_k is the population of the photons, $\Delta\nu_{ks}$ $(= 0.25\ \mathrm{THz})$ is the lasing bandwidth, T $(= 298\ \mathrm{K})$ is the absolute temperature, K_B is the Boltzmann constant, h is the Planck constant,

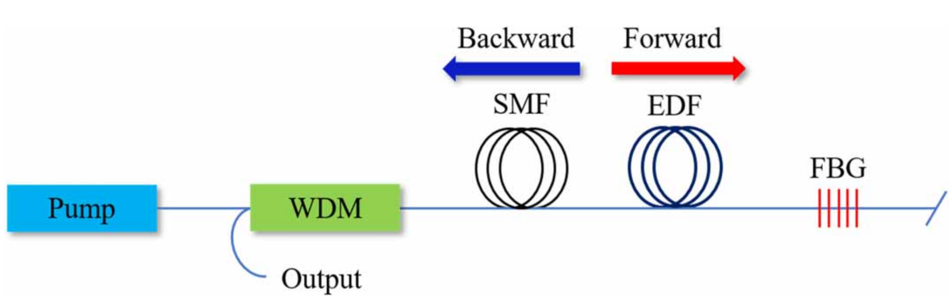

Figure 1. Proposed tuneable hybrid Er-Raman-gain random fibre laser. WDM, wavelength-division multiplexer; EDF, erbium-doped fibre; SMF, single-mode fibre; FBG, fibre Bragg grating.

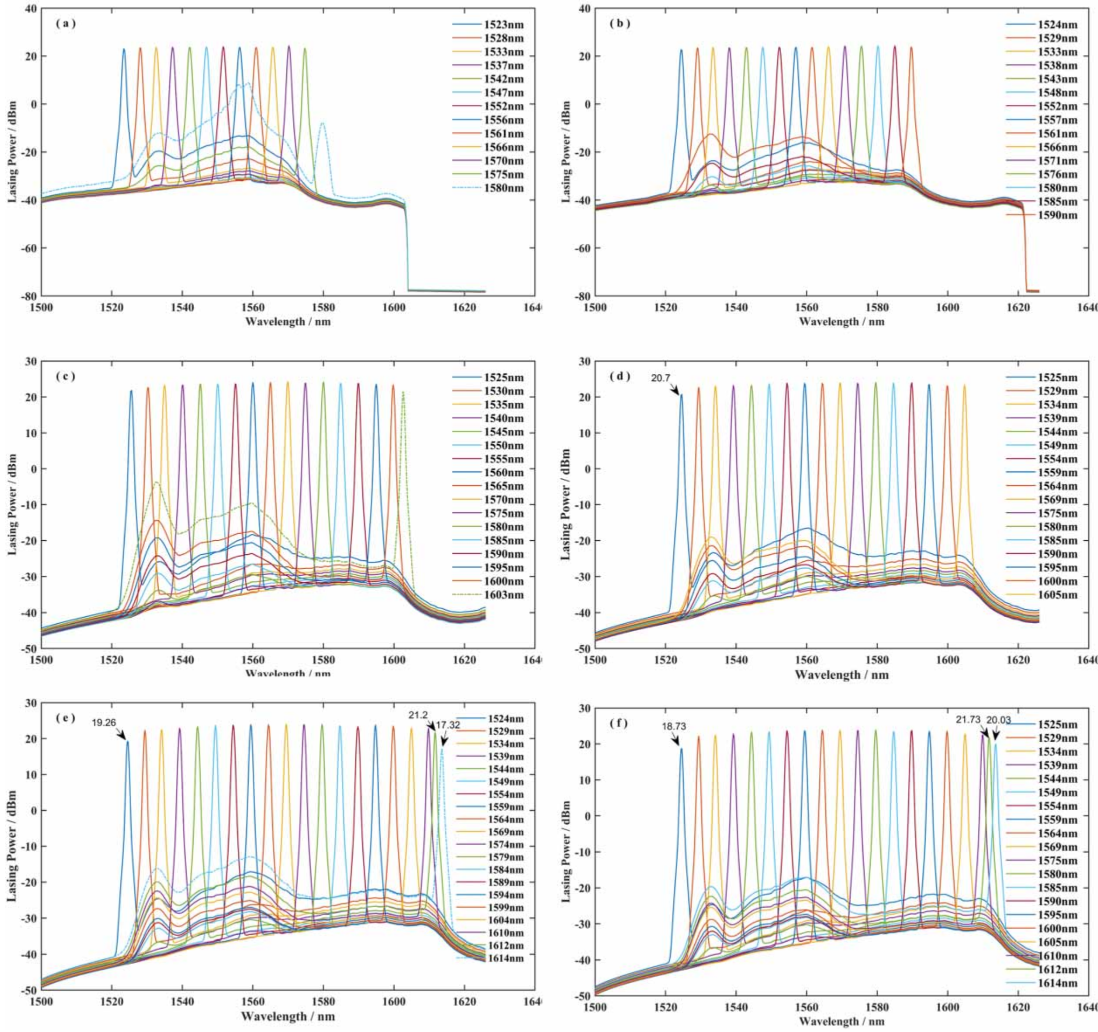

Figure 2. Lasing power spectra with different pump wavelengths: (a) 1455 nm; (b) 1470 nm; (c) 1480 nm; (d) 1485 nm; (e) 1489 nm; (f) 1490 nm.

and ε_k is the Rayleigh scattering coefficient (ϵ_k follows the λ^{-4} law); α_k, g_k are attenuation and gain coefficients obtained from the experiments, respectively.

$$\frac{\overline{N_2}}{\overline{N_t}} = \frac{\sum_{k=0}^{N} \frac{(P_k^+ + P_k^-)\alpha_k}{h\nu_k\zeta}}{1 + \sum_{k=0}^{N} \frac{(P_k^+ + P_k^-)(\alpha_k + g_k)}{h\nu_k\zeta}} \tag{1}$$

$$\frac{dP_k^\pm}{dz} = \pm(\alpha_k^* + g_k^*)\frac{\overline{N_2}}{\overline{N_t}}P_k^\pm \pm 2g_k^*\frac{\overline{N_2}}{\overline{N_t}}h\nu_k\Delta\nu_{ke} \mp (\alpha_k^* + l_k)P_k^\pm \tag{2}$$

$$\frac{dP_k^\pm}{dz} = \mp\alpha_k P_k^\pm \pm \eta g_k(P_o^+ + P_o^-)(P_k^\pm + 0.5\Gamma_k) \pm \varepsilon_k P_k^\pm \mp (1-\eta)\sum_{k=1}^{N}\frac{\nu_0}{\nu_{k'}}(P_{k'}^+ + P_{k'}^- + \Gamma_{k'})P_0^\pm \tag{3}$$

$$\Gamma_k = 4h\nu_k\Delta\nu_{ks}\left\{1 + \frac{1}{exp[h(\nu_0 - \nu_k)/(K_B T)] - 1}\right\} \tag{4}$$

Numerical results and discussion

To investigate the tuning abilities of different pump wavelengths, the length of the SMF was set to 10 km, length of the EDF was set to 12 m, and pump power was set to 1.5 W in the numerical simulation. The reflectivity of the FBG is set to 0.95 and parasitic reflection is set to 0.0001. Equations (1)–(4) were used to numerically simulate the random lasing spectra.

Figure 2 shows the calculated lasing power spectra for different pump wavelengths, where the tuning range gradually increases with pump wavelength increases. With the 1489 nm pump, the tuning range had a width of up to 90 nm (1524–1614 nm). Figure 2(c) shows that

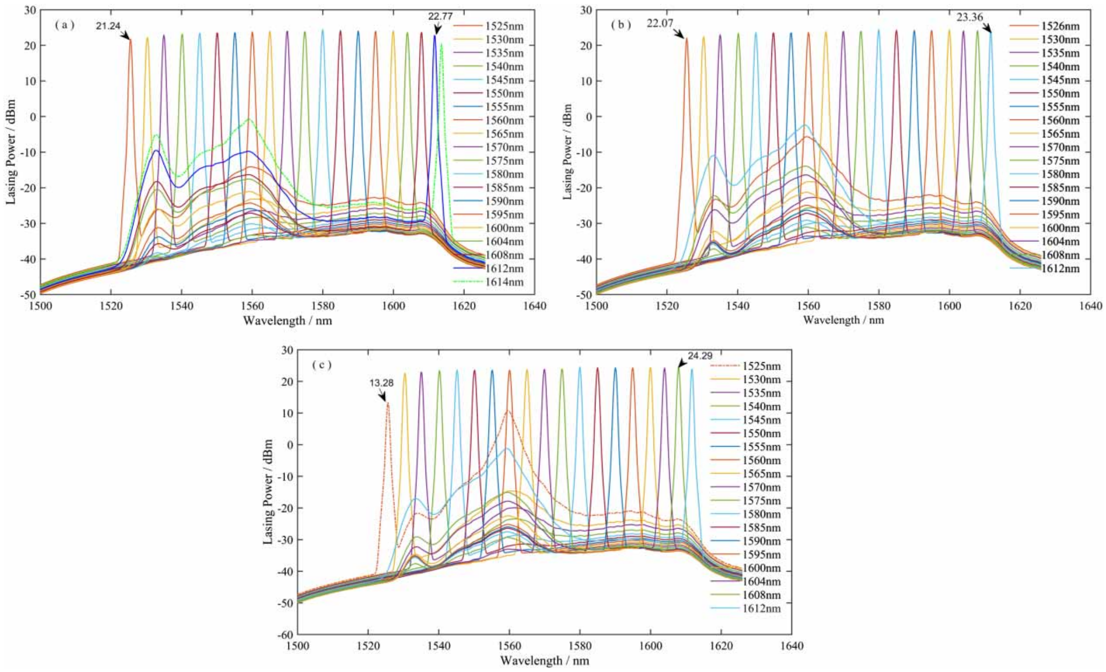

Figure 3. Lasing power spectra with different EDF lengths: (a) 15 m; (b) 18 m; (c) 20 m.

as the pump wavelength increases to 1480 nm, lasing for 1600 nm can be observed for the first time, while the output spectra of the 1590–1605 nm laser have sub-peaks. Figure 2(d) shows that as the pump wavelength further increases to 1485 nm, the lasing powers of the sub-peaks are reduced. For long-wavelength pumping, as shown in Figure 2(d)–(f), the lasing power for 1525 nm is about 2–3 dBm lower than those of other wavelengths. As the pump wavelength increases to 1489 and 1490 nm, as shown in Figure 2(d) and (f), the tuning range increases to a maximum of 90 nm (1524–1614 nm). For the pump wavelength of 1490 nm shown in Figure 2(f), the lasing power at 1525 nm reduces to 18.73 dBm. Therefore, the optimal range of the pump wavelength is 1485–1489 nm.

To study the influence of the EDF length on the laser tuning range, the pump wavelength was set to 1489 nm, pump power was at 1.5 W, and length of the SMF was 10 km. Figure 2(e) shows that when the length of the EDF is 12 m, a tuning range of up to 90 nm can be obtained. As the length of the EDF increases to 15 m, as shown in Figure 3(a), the tuning range is 1525–1612 nm, the lasing powers at all wavelengths increase, and the lasing powers at 1525 and 1612 nm increase by about 1.5–2 dBm each; meanwhile, the power fluctuation greatly decreases by about 1.5 dB. As the length of the EDF increases to 18 m, as shown in Figure 3(b), the lasing power continues to increase by about 0.6–0.8 dBm, and the power fluctuation further decreases to 1.3 dB. Moreover, there are sub-peaks for the lasing power spectra of 1525 and 1612 nm; the sub-peak maximum at 1533 nm is −10.98 dBm, and the sub-peak maximum at 1560 nm is up to −2.34 dBm. When the length of the EDF increases to 20 m, the tuning range narrows to 1530–1612 nm, and the lasing power spectrum does not contain the sub-peak at 1525 nm. Therefore, the optimal length of the EDF is determined as 15 m.

Figure 4 shows the lasing power spectra for different SMF lengths; the pump power is set to 0.9 W for Figure 4(a)–(d), and the pump power is set to 1.5 W for Figure 4(e)–(h), with the length of the EDF being 12 m and pump wavelength being 1485 nm. As the length of the SMF increases, the simulated Raman scattering effect becomes stronger, and the lasing power of the long-wavelength lasers at 1590–1609 nm increase. When the length of the SMF is 10 km, as shown in Figure 4(b) and (f), the widest tuning range is 1524–1605 nm. As the SMF length is increased to 20 or 30 km, as shown in Figure 4(c) and (d), the pump light entering the EDF is weakened; then, the simulated Raman scattering effects are dominant, and the hybrid Er-Raman gain is reduced; thus, the lasing power at 1525 nm further decreases. As shown in Figure 4(g) and (h), when the pump power is 1.5 W, the lasing power spectrum loses some of the shorter wavelength range (1525–1539 nm), and the tuning range is narrowed. Therefore, the optimal length of the SMF is about 10 km.

To study the influence of the pump power on the tuning range, we set the pump power for the results in Figure 5(a) to 0.9 W, Figure 5(b) to 2 W, and Figure 5(c) to 2.5 W, with 1489 nm pump wavelength and EDF length

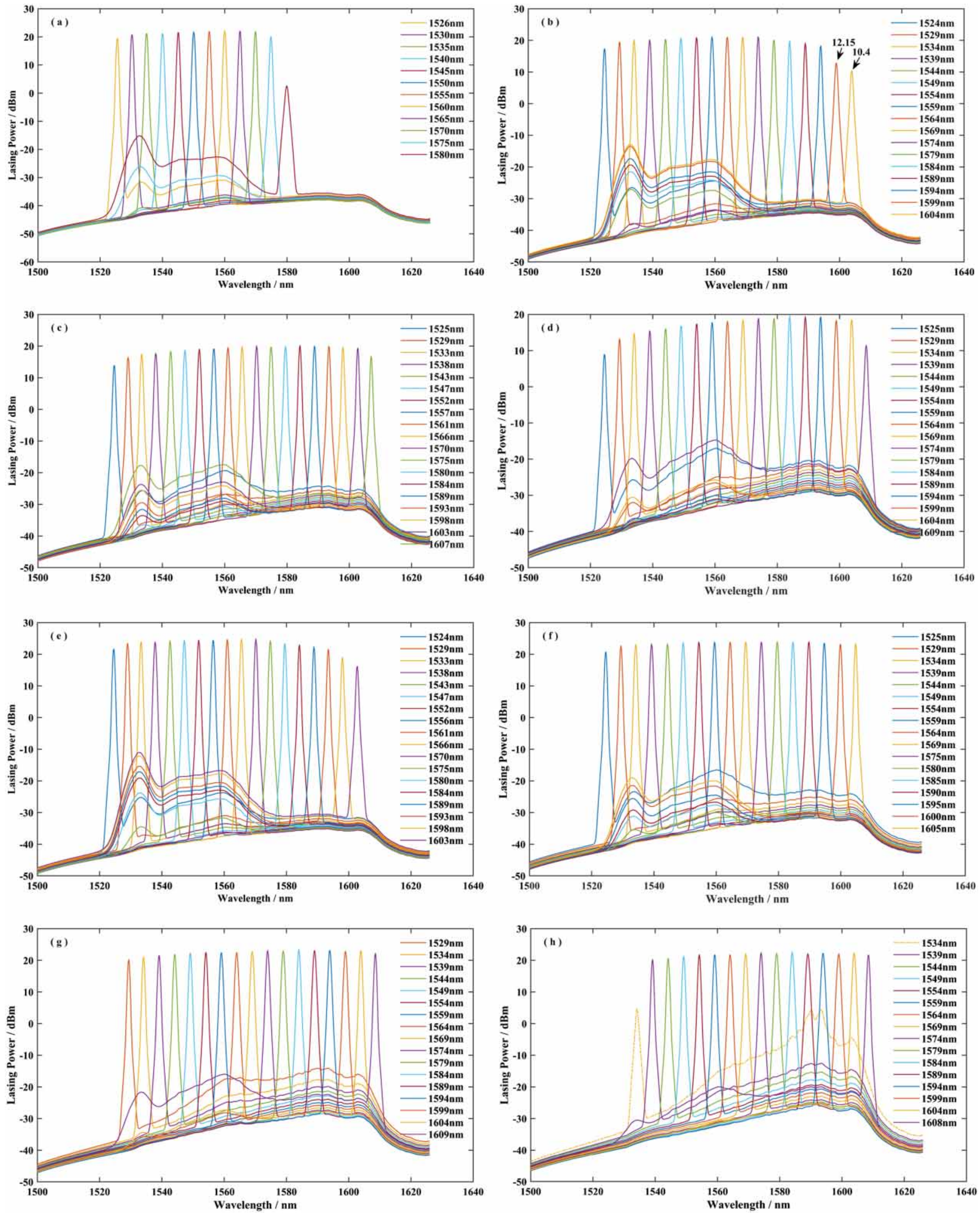

Figure 4. Lasing power spectra with different SMF lengths: (a) 5 km, the 1485 nm pump is set to 0.9 W; (b) 10 km, the 1485 nm pump is set to 0.9 W; (c) 20 km, the 1485 nm pump is set to 0.9 W; (d) 30 km, the 1485 nm pump is set to 0.9 W; (e) 5 km, the 1485 nm pump is set to 1.5 W; (f) 10 km, the 1485 nm pump is set to 1.5 W; (g) 20 km, the 1485 nm pump is set to 1.5 W; (h) 30 km, the 1485 nm pump is set to 1.5 W.

of 15 m. The pump power in Figure 3(a) is 1.5 W for a tuning range of up to 90 nm, while the other parameters are the same as those in Figure 5. The tuning range in Figure 5(a) is 79 nm (1525–1604 nm), and the lasing power spectra sub-peak at 1604 nm has a maximum value of up to −4.232 dBm. As the pump power is increased to 2 W, as shown in Figure 5(b), the tuning range increases to 89 nm (1525–1614 nm). As the pump power increases, the Raman effect becomes stronger, and the sub-peak maximum shifts towards a wavelength of 1560 nm. As the pump power increases to 2.5 W, as shown in Figure 5(c), the tuning range narrows to 83 nm

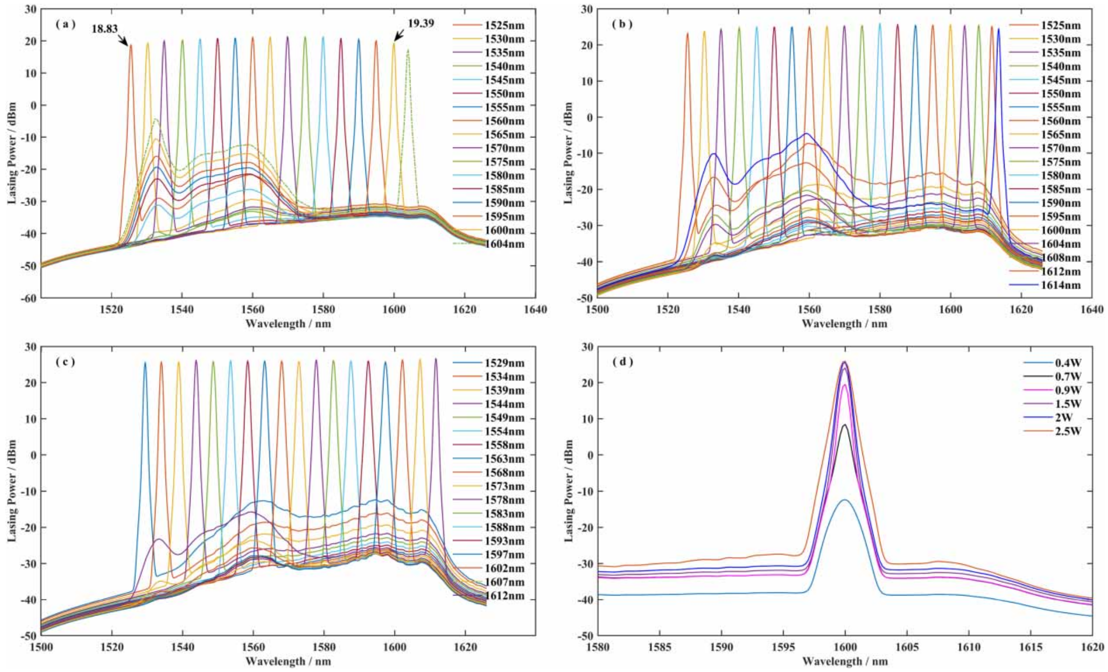

Figure 5. Lasing power spectra with different pump power values: (a) 0.9 W; (b) 2 W; (c) 2.5 W; (d) lasing power spectra at 1600 nm.

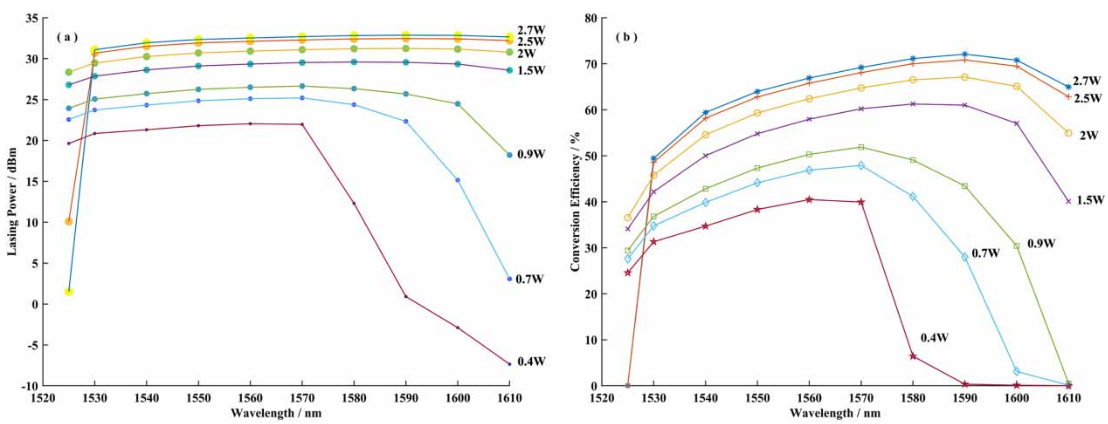

Figure 6. (a) Lasing power discrete value with 1489 nm pump wavelength; (b) optical conversion efficiency with different pump power values.

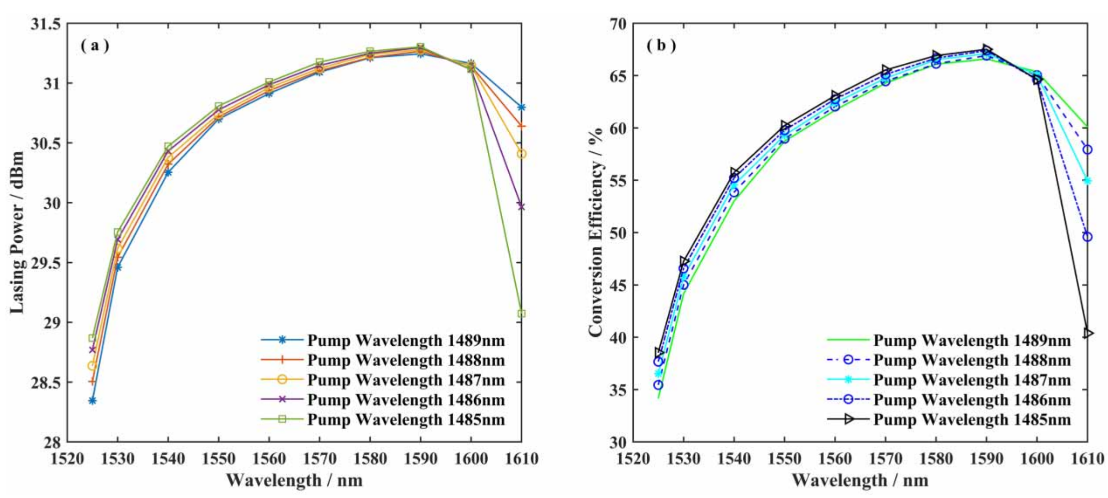

Figure 7. (a) Lasing power spectra and (b) optical efficiency with pump wavelengths ranging from 1485 to 1489 nm.

(1529–1612 nm). Figure 5(d) shows that the lasing power spectra at 1600 nm have obvious threshold characteristics. At a pump power of 2 W, the lasing power is 25.91 dBm and OSNR is 56.44 dB.

Finally, the lasing power and optical conversion efficiency of the laser were investigated after eliminating the ASE noise. Figure 6(a) shows the discrete values of the lasing power for the 1489 nm pump for an SMF length of

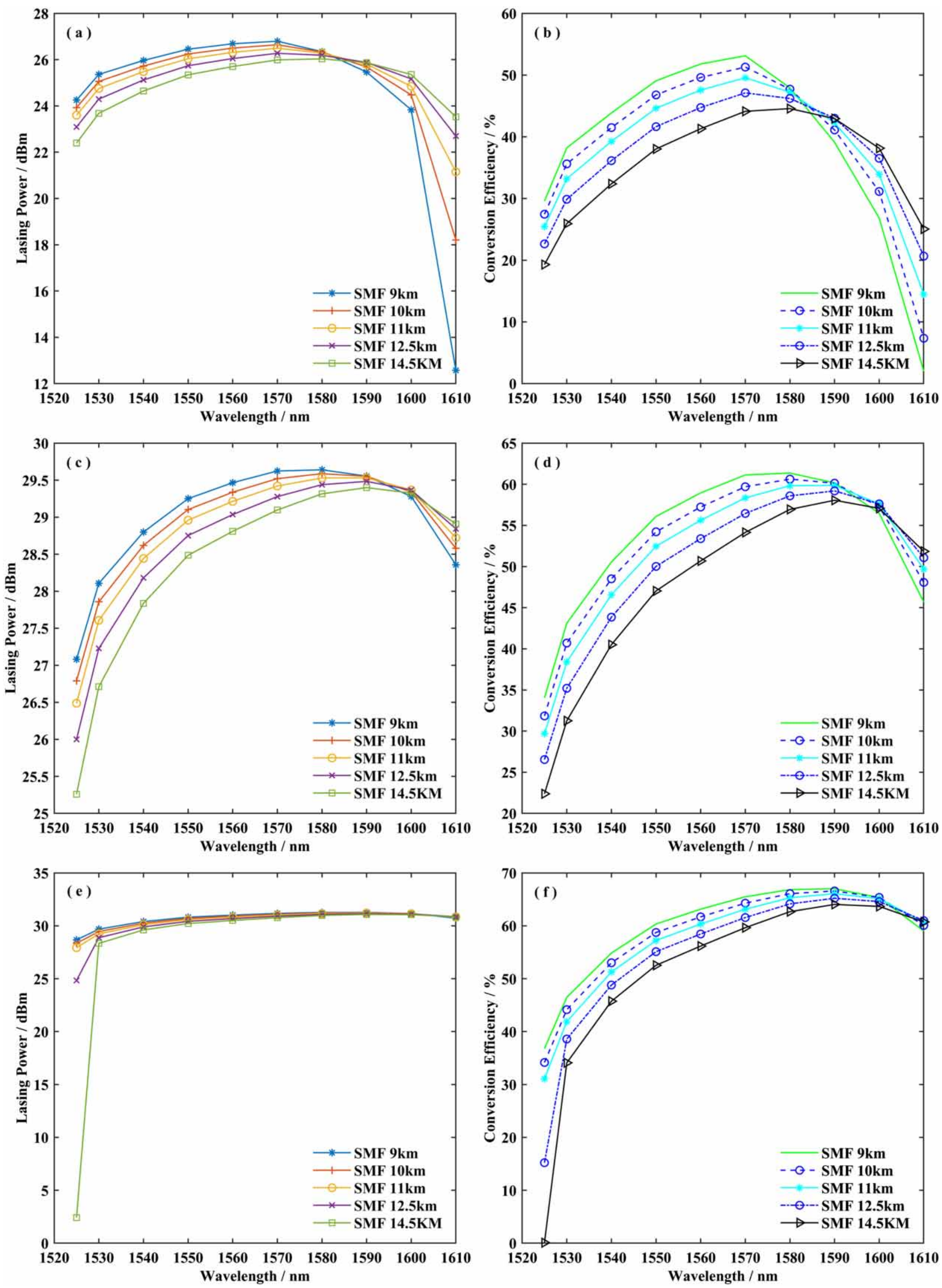

Figure 8. (a, b) lasing power spectra and optical conversion efficiency with 0.9 W pump power, respectively; (c, d) lasing power spectra and optical conversion efficiency with 2 W pump power, respectively; (e, f) lasing power spectra and optical conversion efficiency with 2.5 W pump power, respectively.

10 km and EDF length of 15 m. Figure 6(b) indicates that the maximum optical conversion efficiency for a pump power of over 1.5 W is achieved at a lasing wavelength of 1600 nm. When the pump power is 2.7 W, the lasing power at 1600 nm is 1.92 W, and the optical conversion efficiency is 71.1%.

Figure 7 shows the lasing power spectra and optical conversion efficiencies for different pump wavelengths (1485–1489 nm) and a pump power of 2 W. It is seen that with the 1485 nm pump, the lasing power and optical conversion efficiency are highest in the range of 1525–1590 nm. However, with the 1489 nm pump, the lasing power and optical conversion efficiency were highest in the range of 1590–1610 nm. The maximum optical conversion efficiency at 1590 nm is 67.39% with a 2 W pump power for a lasing power of 31.3 dBm, which indicates that the optimal pump wavelength is 1489 nm.

Figure 8 shows the discrete spectrum of the lasing power and optical conversion efficiency for different SMF lengths and 1489 nm pump wavelength; the pump power in Figure 8(a) is 0.9 W, Figure 8(b) is 1.5 W, and Figure 8(c) is 2 W. Considering the lasing powers and optical conversion efficiencies of the C and L bands together (in the range of 1590–1610 nm), the optimal length of the SMF is 10 km.

Conclusions

In this work, we propose a detailed investigation to realize the maximum tuning range of a hybrid Er-Raman-gain RFL by adjusting the pump wavelength, pump power, and lengths of the SMF and EDF. Theoretical simulation results denote that by using erbium-Raman hybrid gain, this scheme has a wide tuning range of up to 90 nm (1524–1614 nm) with high OSNR ($>$ 50 dB). This optimization allowed reduction of the lasing power fluctuations greatly. A high optical conversion efficiency of 71.1% can be achieved with a pump power of 2.7 W. Compared to the previous Raman gain or Er-doped gain RFLs, the optimized erbium-Raman hybrid gain RFL can not only broaden the wavelength tuning range but also realize high-efficiency output. The concept of combining both Raman gain and Erbium-doped gain to obtain a maximum tuning range provides an effective method of optimizing a widely tuneable RFL, which could inspire new explorations of novel schemes for random fibre lasers.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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