Multiwavelength Raman fiber ring laser with the spectrum profile broadened by parametric four wave mixing in highly nonlinear dispersion-shifted fibers

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A broadband multiwavelength Raman fiber ring laser (RFRL) covering the whole C-band at room temperature are presented. The effect of the intracavity highly nonlinear dispersion-shifted fiber on broadening and flattening the output spectrum envelope is discussed and experimentally demonstrated. More than 45-dB extinction-ratio multiwavelength output from 1527.76 to 1566.86 nm with 100-GHz channel spacing and 2.1-dB power ripple has been achieved by carefully controlling the individual powers of three pump lasers.

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Stable continuous wave (CW) multiwavelength fiber lasers have been investigated extensively in recent years due to their wide applications in wavelength division multiplexing (WDM) optical communication systems, fiber sensing, fiber-optical components testing, and so on[1]. The initial attention was focused on the rare-earth-doped fiber lasers, especially on erbium-doped fiber (EDF) lasers (EDFLs), where special means are required for stable multiwavelength operation due to the relatively broad homogeneous linewidth of EDF at room temperature. The approaches proposed include cooling the EDF to liquid nitrogen temperature in order to reduce the homogeneous linewidth[1] or introducing the intracavity frequency shifting to prevent single mode laser oscillation[2]. Recently, hybrid Brillouin/EDFLs have been demonstrated as an efficient method to generate 10- and 20-GHz laser combs via various techniques for cascading the Stokes shifting process[3,4]. However these methods increased the complexity in source configuration. For simplification, the multiwavelength lasing at room temperature based on Raman fiber lasers (RFLs) would be one of the strong competitors due to the inhomogeneously broadened gain characteristic of stimulated Raman scattering (SRS)[5]. The first multiwavelength Raman fiber ring laser (RFRL) was reported in 2001[6], the output of which included 8 channels over a spectral span of 5.6 nm with 10-dB flatness. Lately, a CW depolarized multiwavelength RFRL with 58 channels within 3-dB bandwidth of 23.8 nm was obtained by using three-wavelength pumping[7]. In this letter, a broadband multiwavelength RFRL is demonstrated in which the Raman gain is provided by a piece of dispersion compensating fiber (DCF) and a length of highly nonlinear dispersion-shifted fiber (HNL-DSF) is also introduced for the spectrum broadening. Experimental results with and without the HNL-DSF are analyzed and compared. 50 lasing channels with 2.1-dB power ripple over 39.1 nm range (1527.76–1566.86 nm) are achieved.

The experimental setup of the multiwavelength RFRL is shown in Fig. 1. The Raman gain fiber is a 10-km-long DCF with three-wavelength dual-direction pumping. The main parameters for DCF are 0.60 dB/km of attenuation, 2.278 (1 $\mathrm{W}^{-1}\mathrm{km}^{-1}$) of peak Raman gain coefficient, and −96.94 ps/nm of chromatic dispersion at 1550 nm. The three pump wavelengths are 1440 nm (forward) provided by two polarization-multiplexed semiconductor laser diodes (LDs), as well as 1425 and 1454 nm (backward) provided by a commercial adjustable three-wavelength cascaded RFL (Gainstar RGM310, Laser-Sharp Inc.) operated in two-wavelength mode. WDM1 and WDM2 are two 1480/1550 nm WDM dielectric couplers. An optical isolator is inserted to ensure stable unidirectional oscillation. 1.45 km of HNL-DSF is spliced between WDM2 and the isolator. For maximizing the effect of spectrum broadening, the zero-dispersion wavelength of HNL-DSF should locate in the exciting region of the Raman laser. The HNL-DSF has a zero-dispersion wavelength $\lambda_0 = 1535.65$ nm and a nonlinear refractive index $n_2 = 2.8 \times 10^{-20}$ m^2/W, as well as 0.73-dB/km attenuation, 0.22-ps/(nm·km) chromatic dispersion, 0.0155-ps/(nm^2·km) dispersion slope, and 3.9-μm mode field diameter at 1550 nm, specified by the manufacturer. The C/L band WDM is used to withdraw the L-band light from the oscillation, which will be interpreted further later. A fiber Fabry-Perot based comb filter (FFPF) acts as the wavelength-selective component. This filter has a 100-GHz free-spectral range, 2.5-GHz 3-dB bandwidth, 28-dB contrast, and < 2-dB insertion loss.

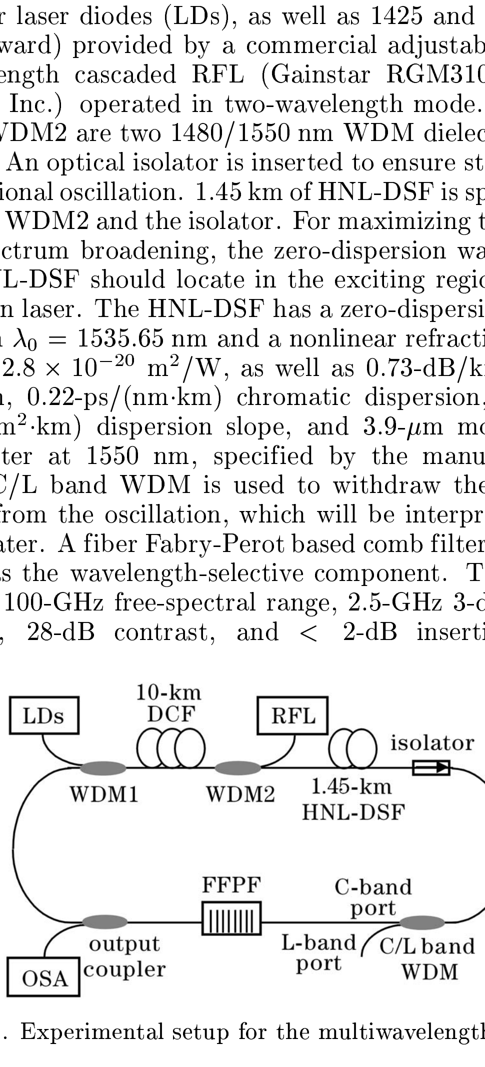

Fig. 1. Experimental setup for the multiwavelength RFRL.

A broadband fiber coupler was used to extract ~10% of the oscillation from the ring cavity. The roundtrip loss of the ring cavity was measured to be 8.8 dB without the FFPF and HNL-DSF. The output optical power and spectrum are measured by using an optical spectrum analyzer (OSA) with resolution of 0.02 nm.

In order to identify the effect of the HNL-DSF on the multiwavelength RFRL, firstly, we measured the output spectra before the HNL-DSF was spliced. In this case, as the pump power increased the cascaded SRS effect was remarkable and the energy was transferred from pumps to the first-order Stokes component centered at 1540 nm, and in turn, to the second one around 1670 nm. To maximize the number of lasing channels and the output spectrum flatness, we used the C/L band WDM to remove the second-order Stokes light and restrict the energy within the first-order. Meanwhile, the pump powers were adjusted properly so that the flattest spectrum was obtained. Figure 2 shows the output spectrum and the extinction ratio (ER) of channel peaks to the background for the pump powers of 403, 340, and 106 mW at 1425, 1440, and 1454 nm, respectively. It is easy to distinguish between the lasing and non-lasing channels by the large ER difference. There were totally 41 lasing channels over the spectral range from 1524.624 to 1556.284 nm, and each of them has an ER greater than 50 dB. Centered at 1538.696 nm was a notch with ~ 5-dB depth from the peak. The total output power was measured to be 9.467 mW.

Then the HNL-DSF was spliced and the measurement was repeated. As the Raman amplified light wave propagated through the HNL-DSF, strong four wave mixing (FWM) interaction occurred due to the low dispersion and high nonlinearity. Through the FWM interaction, the energy was transferred from the higher peaks to the lower channels, which leads to the output spectrum to be broadened and smoothed. Figure 3 is the measured broadband multiwavelength output spectrum when the pump powers were 399, 246, and 541 mW at the three pump wavelengths, respectively, and the C/L-band WDM was removed. Under this condition, there was no second-order SRS peak observed because introducing the HNL-DSF added 2.8 dB of cavity loss. So the intracavity power was lower. Moreover, the spectral broadening reduced the spectral power density and would suppress the cascaded SRS effect further. For this case the C/L band WDM was not necessary for breaking the second-order Stokes but may hinder the spectrum from extending to the longer wavelength range. Both output spectrum and power were very stable. Although the output power was only 3.701 mW, about 4 dB lower than that in the case without HNL-DSF, but the output spectrum was broadened and smoothed. The 39.1-nm flat top range from 1527.76 to 1566.86 nm has a ripple less than 2.1 dB and includes 50 channels. To the best of our knowledge, this is the widest spectral coverage ever achieved in the multiwavelength fiber lasers. The spectral ER is more than 45 dB for each channel in this region and decreases gradually from the center to both sides. The channels with ER greater than the contrast of FFPF total up to 106. The parametric amplified background noise that generated in HNL-DSF would be responsible for the ER deterioration[8]. Anyway, 45-dB ER is enough for applications such as component characterization and fiber sensing.

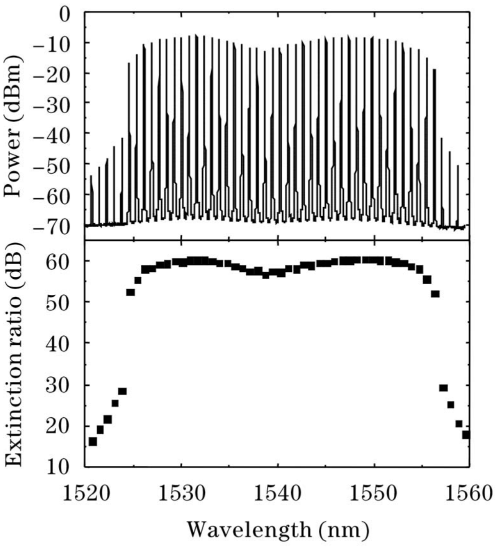

Fig. 2. Output spectrum (top row) and extinction ratio of channel peak to background (bottom row) of multiwavelength RFRL without HNL-DSF in the cavity.

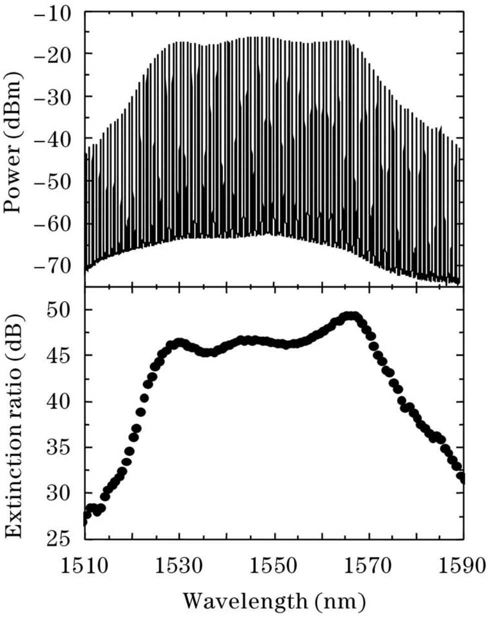

Fig. 3. Output spectrum (top row) and extinction ratio of channel peak to background (bottom row) of multiwavelength RFRL with HNL-DSF in the cavity.

The self-beating spectrum of one of the lasing channels for single peak was measured using a tunable bandpass filter (−3-dB bandwidth of 0.6 nm), a photodetector (20-GHz bandwidth) and an electrical spectrum analyzer (HP8593E, 9 kHz—26.5 GHz). Figures 4(a) and (b) show the results for the cases without and with the HNL-DSF inside the cavity, respectively. From the radio frequency (RF) spectra we evaluate that the relevant linewidths at −3 dB are 500 MHz and 2.228 GHz, respectively. As expected the linewidth is broadened obviously and approaches the transmission linewidth of the FFPF due to the enhanced intra-channel FWM effect when

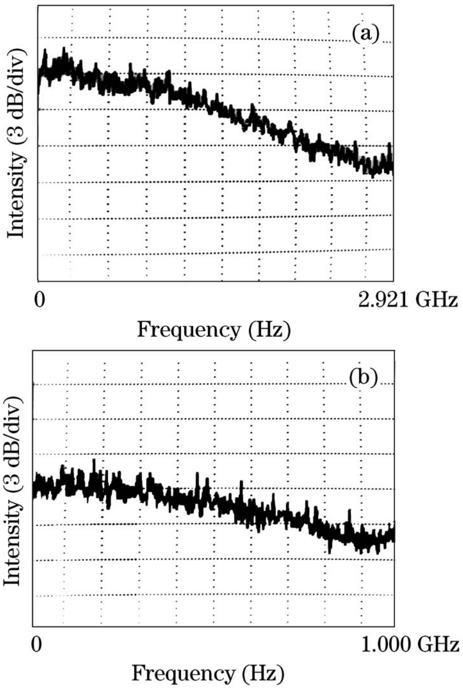

Fig. 4. Self-beating RF spectra of one lasing channel without (a) and with (b) HNL-DSF in the ring cavity.

the HNL-DSF is included in the cavity. Since the longitudinal mode structure is visible in the highly resolved frequency range, we can confirm that this multiwavelength source is in fact a laser. Considering that the modes spacing is about 18 kHz, one lasing channel contains numerous cavity modes. The fact prevents this laser from being used as a telecommunication transmitter, but it can be adequate for component characterization and fiber sensing, where the requirement of the linewidth is not severe.

It must be emphasized that our experimental setup was not optimized for the output power but for as many as possible lasing channels. It would be possible to increase the output power by increasing the output ratio at the coupler. However, increasing the output ratio is equivalent to increasing the cavity loss, so the intracavity power is inevitably decreased, which would lead to weaker nonlinear effects in the HNL-DSF and hence fewer lasing channels.

We demonstrated a room temperature multiwavelength RFRL. The gain was provided by 10-km DCF pumped by 399, 246, and 541 mW at 1425, 1440, and 1454 nm respectively, and the spectrum profile was broadened by parametric FWM effects in an unpumped 1.45-km HNL-DSF. 50 channels with a spectrum ripple of 2.1 dB cover 39.1-nm wavelength range from 1527.76 to 1566.86 nm. The total output power was 3.701 mW. However, the output power can be enhanced by optimizing the ring cavity design, and the wavelength range can be expanded by adding one or more pump wavelengths properly.

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