Actively mode-locked fiber ring laser based on photonic crystal fiber

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A wavelength tunable, high repetition rate mode-locked fiber ring laser was demonstrated. In the experiment, photonic crystal fiber (PCF) is used as an intracavity compression medium. The high nonlinearity and anomalous dispersion of PCF can cause intracavity compression and result in significant reduction in the pulse width. The pulses duration at the repetition rate of 9.99 GHz was less than 10 ps over the range of 1532—1565 nm.

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In contrast with conventional optical fibers, the photonic crystal fibers (PCFs) have three main merits: firstly, their cross-section can be optimized to obtain single mode operation on a wide wavelength range[1]. Secondly, PCF with a very small core can exhibit very high nonlinear properties[2]. Finally, dispersion characteristics in PCFs can be easily shaped due to the flexibility of varying air-hole size and the position in the photonic cladding[3]. Since the first PCF was reported by Knight *et al.* in 1996[4], PCFs are subject to intense research because of their exceptional optical properties. In optical communications, the researches in supercontinuum generation, optical parametric amplification, and soliton compression of PCFs were investigated[5−8].

In this letter, we demonstrated an active mode-locked fiber ring laser in which a 25-m PCF was used for intracavity nonlinear pulse compression medium. The pulses at the repetition rate of 9.99 GHz with less than 10 ps duration were obtained under the interaction of high nonlinearity and suitable anomalous dispersion in PCF. The output pulses can be tuned from 1532 to 1565 nm.

Figure 1 shows the schematic diagram of the actively mode-locked fiber ring laser based on PCF. The optical gain is provided by a commercial erbium-doped fiber amplifier (EDFA) (Keopsys Co., France). The performance parameters are: the output saturated power is 30 dBm, small signal gain is more than 45 dB, noise figure is less than 6 dB, optical bandwidth is 1531—1565 nm. The isolator allows the light to propagate along one direction only in the cavity. The optical coupler, which couples 10% of the output of the ring cavity, is provided by Accelink Technologies Co., Ltd. An OTF-300 optical tunable filter (Santec Co.) is used to select the central wavelength. The performance parameters are as follows. Wavelength tunable range is 1530—1570 nm, 3 dB bandwidth is 0.65 nm, and insert loss is 2.5 dB. The $LiNbO_3$ Mach-Zehnder modulator is made by Corning, whose 3-dB bandwidth, insert loss, half wavelength voltage are 4 GHz, 3.5 dB, and 6.8 V, respectively. A pulse pattern generator provided by Anritsu generates a signal that is subsequently divided into two branches. One branch is electrically amplified and is used to drive the $LiNbO_3$ intensity modulator in the cavity. The other branch is sent into the oscilloscope. Spectral and temporal characteristics of the output pulses are measured using an optical spectrum analyzer with 0.1-nm resolution and 40-GHz oscilloscope.

Figure 2 shows the center micrograph of the PCF which is provided by crystal fiber A/S. Air filling fraction in the holey region is more than 90%, hence the guide mode is strongly confined into the defect. The zero dispersion

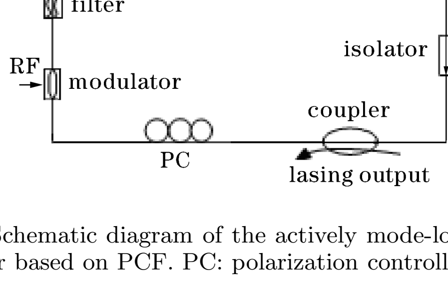

Fig. 1. Schematic diagram of the actively mode-locked fiber ring laser based on PCF. PC: polarization controller.

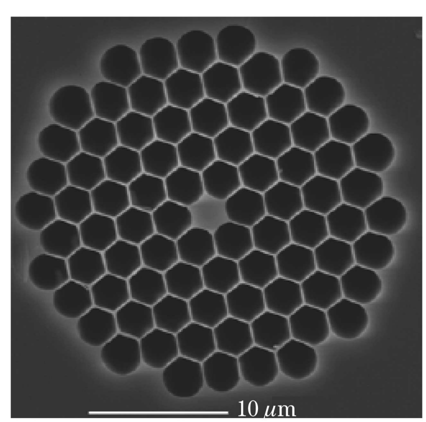

Fig. 2. Center micrograph of PCF.

wavelength of the fiber was about 800 nm. The diameters of outer silica cladding and the coating are 105 and 230 μm, respectively. The core diameter (average) and the pitch (distance between cladding holes) are 2.4 and 2.9 μm, respectively. The fiber has a dispersion parameter of 164 ps/(nm·km), a nonlinear coefficient of 36 $W^{-1}\cdot km^{-1}$, and a loss coefficient of 40 dB/km (at 1.55 μm). Both ends of the PCF were fusion-spliced to a single mode fiber, which yielded a loss of 3.5 dB.

In the experiment, the spectral broadening was seen. Because the high power density in the core is one of the most important factors resulting in spectral broadening, we investigated the dependence of spectral width on the optical power and the dependence of spectral width on the wavelength. On a certain time, with the wavelength of 1564.2 nm, the dependence of the spectral width on the optical power in the cavity is shown in Fig. 3. As can be seen from it, in general speaking, when the average power is higher, the spectrum becomes wider. When the average power is in the range of 2.1—4.9 mW, the spectral width increases slowly. When the average power is in the range of 4.9—6.7 mW, the spectral width increases rapidly. But when the average power is above 6.7 mW, the spectral width decreases.

It is evident that there are two stages for spectral broadening. In the first stage, when the average power is in the range of 2.1—4.9 mW, the spectrum broadens slowly because of the combined effects of self-phase modulation and anomalous dispersion. At the second stage, when the average power is in the range of 4.9—6.7 mW, the spectrum broadens rapidly. This is mainly because that in the nonlinear media, the refractive index of media is related with intensity of incident light. With the increase of peak power of the pulse, the nonlinear effects increase. The spectral broadening is resulted from several nonlinear effects of self-phase modulation, cross-phase modulation, and four-wave mixing.

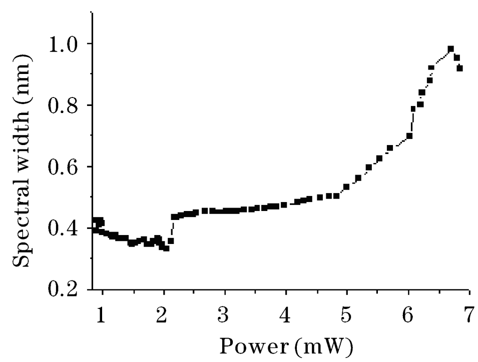

Fig. 3. Dependence of the spectral width on the optical power with the wavelength of 1564.2 nm.

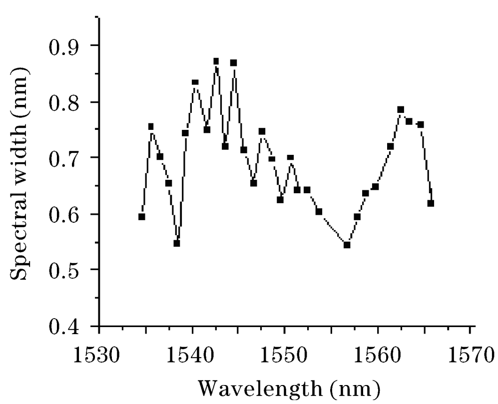

Fig. 4. Dependence of the spectral width on the wavelength with the average power of 5.9 mW.

The spectrum in the range of 1531—1565 nm can be tunable in the experiment. When the average power in the cavity is 5.9 mW, the dependence of the spectral width on the wavelength is measured as is show in Fig. 4. We can see from it, the widest spectral width is 0.86 nm at the wavelength of 1544.6 nm.

In the experiment, the stably mode-locked pulse can be obtained by adjusting the position of the polarization controller (PC) and reduce the loss in the cavity. At the time, direct current bias applied on the modulator and the repetition rate are 8.9 V and 9.99 GHz, respectively. Figure 5 shows the spectrum of the mode-locked pulses with 1564.1-nm spectral width. Figure 6 shows the corresponding mode-locked pulse trains. The cursorily measured pulse duration is 11 ps. Taking account of the response time of the oscilloscope, the actual pulse duration is less than 10 ps. The average power measured by the optical power meter is 6.1 mW.

In this letter, a section of PCF is introduced into the cavity of the actively mode-locked fiber ring laser, which acts as an intracavity compression medium. In this way, stable, and high repetition rate can be obtained. Contrasting with the scheme using dispersion shifted fiber to compress the pulse, this fiber length is shorter. Contrasting with the scheme using sagnac loop to compress the pulse, this structure is compact and simpler. In the future, this simple and compact scheme will have extensive

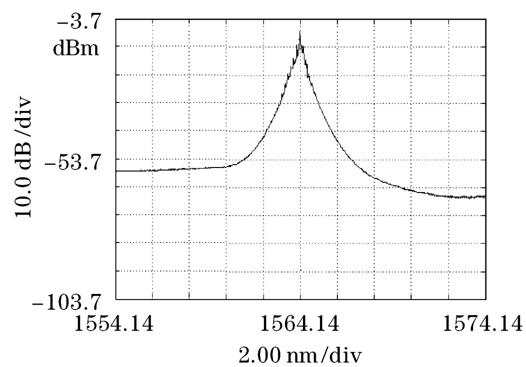

Fig. 5. Spectrum of the mode-locked pulse.

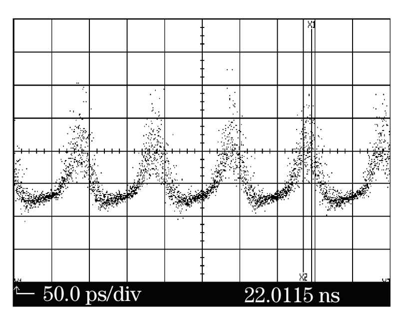

Fig. 6. Mode-locked pulse trains.

applications in wavelength division multiplexing/optical time demain-multiplexing (WDM/OTDM) system.

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