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Generation of wideband tunable femtosecond laser based on nonlinear propagation of power-scaled mode-locked femtosecond laser pulses in photonic crystal fiber*

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We implement an experimental study for the generation of wideband tunable femtosecond laser with a home-made power-scaled mode-locked fiber oscillator as the pump source. By coupling the sub-100 fs mode-locked pulses into a nonlinear photonic crystal fiber (NL-PCF), the exited spectra have significant nonlinear broadening and cover a spectra range of hundreds of nm. In experiment, by reasonably optimizing the structure parameters of NL-PCF and regulating the power of the incident pulses, femtosecond laser with tuning range of 900–1290 nm is realized. The research approach promotes the development of femtosecond lasers with center wavelengths out of the traditional laser gain media toward the direction of simplicity and ease of implementation.

Keywords: power-scaled mode-locking laser, photonic crystal fiber, wide tunability, femtosecond pulse

PACS: 42.55.–f, 42.55.Wd, 42.81.–i, 42.65.–k **DOI:** 10.1088/1674-1056/abe231

1. Introduction

Over the last several decades, ultrashort pulse lasers with diverse laser characteristics[1–3] have been extensively studied and developed so as to meet multifarious requirement of fundamental science and application fields.[4,5] In addition to power scaling,[6] energy increment,[7] and pulse shortening,[8] wavelength tuning of the laser source is also an important research subject for laser community, which enables wide use of ultrafast lasers in different fields of discipline.[9–11] For instance, in multi-photon fluorescence microscopy, tunable femtosecond lasers operating in the near-infrared spectral regime enable the excitation of most of the applicable fluorescent proteins. As a result, these kinds of lasers are much desired *in vivo* noninvasive dynamic observations due to performance advantages in promoting imaging resolution, increasing penetration depth, and improving visualization. In addition, in brain science, life science, etc., due to the typical peak absorption at 920 nm, so femtosecond lasers centered 920 nm are able to efficiently excite most of the frequently-used bio-sensors, such as Alexa Fluor 488, enhanced green fluorescent proteins (EGFP), and GCaMP6 indicator,[12–14] and have important research significance.

In general, besides optical parametric oscillation (OPO),[15] supercontinuum generation (SCG),[16] Cherenkov radiation (CR),[17] and passively mode-locking (PML),[18] the realization scheme of wideband tunable femtosecond lasers also contains nonlinear spectra broadening in nonlinear fiber and the followed effective spectral selectivity technique. The operation principle can be described as following: when the femtosecond pulses propagate along a nonlinear fiber, due to the high peak power and the resultant nonlinear effects, such as self-phase modulation, self-steeping, and stimulated Raman scattering, the exited spectra from the nonlinear fiber are broadened to hundreds of nm. At the same time, the spectra also have high coherence. Subsequently, by effective slicing in the spectral domain using a spectra filter with optimal transmission wavelength and bandwidth, femtosecond laser with center wavelength different from that of the incident pulses can be generated in a wide tuning range. In comparison with OPO, SCG, CR, and PML, the above technical scheme has lots of advantages in reliability, compactness, and ease of operation. Moreover, the above technical scheme overcomes the precise synchronization in OPO laser, low coherence in SCG, selective dispersion in CR, and limited wavelength tuning in PML, etc.

Based on the above mentioned operation principle, by propagating the amplified Yb-fiber femtosecond pulses through a nonlinear photonic crystal fiber (NL-PCF), laser output tunable from 1030 nm to 1215 nm was reported.[19] With a high-average-power Er-fiber amplifier as the pump source, laser output tunable from 1.3 μm to 1.7 μm has been realized.[20] Recently, in combination with frequency doubling in PPLN, a tunable laser source in the visible spectral region has also been presented.[21] However up to now, these

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research works mainly focused on the use of amplified femtosecond laser configurations.[19–22] In comparison with fiber chirped pulse amplifiers, mode-locked femtosecond fiber oscillators with comparable power output have advantages of compact configuration and low-cost. More importantly, the mode-locked fiber lasers have negligible nonlinear dispersion, much higher pulse fidelity and can potentially facilitate the generation of nonlinear spectra with much higher coherence and much wider spectra coverage. Therefore, using power-scaled mode-locked fiber oscillators as the pump source rather than the complicated amplification configurations provides an effective solution and technical proposal to generate wideband tunable femtosecond laser source with simplicity and ease of implementation, and has important research significance.

Therefore in this work, utilizing a home-made sub-100 fs power-scaled mode-locked fiber oscillator as the pump source, we innovatively carry out an experimental research for the generation of wideband tunable femtosecond laser. By exploring the effect of NL-PCF structure parameters and incident pulse power on nonlinear spectral broadening and laser characteristics of the new wavelength pulse generation, a tuning range of 390 nm is experimentally obtained.

2. Experimental setup

The experimental setup used to generate wideband tunable femtosecond laser output is schematically shown in Fig. 1. It mainly consists of a home-made high-average-power mode-locking fiber oscillator, 1000 lines/mm transmission grating-pair, a half-wave plate (HWP), a polarization beam splitter (PBS), a section of commercially available NL-PCF, and spectral filters (SFs) with different central wavelengths. The mode-locked fiber oscillator can stably deliver 4 W of average power at 63.2 MHz repetition rate. The central wavelength lies at 1044 nm and the spectra span from 1024 nm to 1064 nm. Laser pulses can be compressed to sub-100 fs from 7.4 ps. After the transmission grating-pair compressor, average power of 3.2 W is obtainable. Then, the femtosecond pulses are coupled into NL-PCF with the use of a 12 mm focal length lens. The average power can be adjusted based on the combination of HWP and PBS. The incident femtosecond pulses cause significant spectral broadening with its propagation in NL-PCF and the exited spectra present a multi-peak distribution that serves as the direct spectral source for wideband tunable femtosecond laser generation after the spectral filter. Except for the incident power, for generation of wideband tunable femtosecond laser, the pulse width is also an important influence factor. In this work, considering that the pulse duration of the incident laser nearly approaches to its transform-limited width, we concentrate our research work on the effect of the NL-PCF structure parameters and incident power on the tuning range. Under the equivalent incident power, pulses with shorter temporal widths are beneficial for realization of new wavelength laser with much shorter pulse width and wider tuning range.

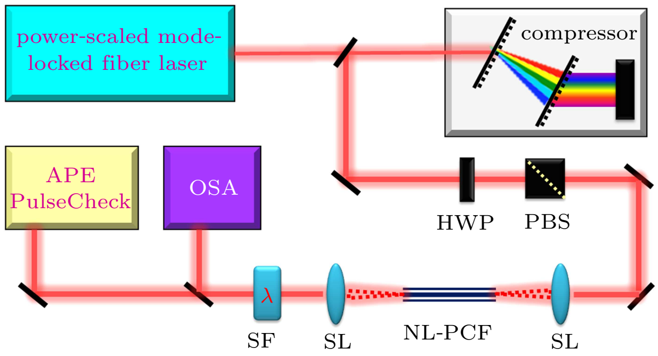

Fig. 1. Experimental setup of the wideband tunable femtosecond laser source. HWP: half-wave plate; PBS: polarization beam splitter; SF: spectral filter; OSA: optical spectrum analyzer; SL: spherical lens; NL-PCF: nonlinear photonic crystal fiber.

3. Results and discussion

In order to study the influence of the NL-PCF parameters, such as length and mode field diameter (MFD), on spectral broadening characteristics of the incident pulses, we implement comparative experiment research using NL-PCFs with different parameters. It contains two cases: one is the same length, but different MFDs; and the other is the same MFD, but different lengths. Figure 2 illustrates the experiment results.

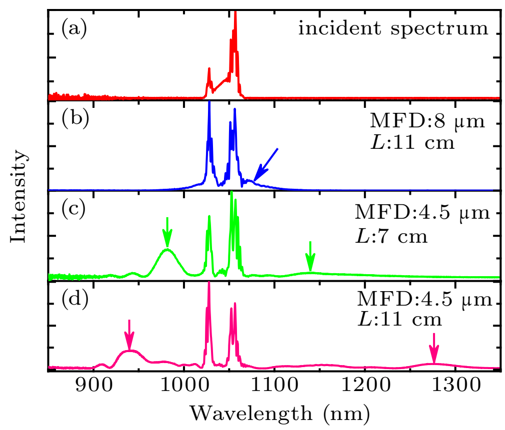

Fig. 2. (a) Initial spectra of the incident pulses; nonlinear broadened spectra for (b) PCF with 8 μm MFD and 11 cm length, (c) PCF with 4.5 μm MFD and 7 cm length, and (d) PCF with 4.5 μm MFD and 11 cm length.

From Figs. 2(b) and 2(d), we can clearly see that under the same length condition, the wider spectra broadening is obtained for the PCF with smaller MFD when the coupled power is 1.1 W. The spectra coverage ranges from ∼ 100 nm (MFD: 8 μm) to ∼ 400 nm (MFD: 4.5 μm) as a result of the enhanced nonlinear effects. Moreover, as shown in Figs. 2(c) and 2(d), increasing the interaction length is also an effective method to broaden the output spectrum under the same coupled power of 1.1 W. In experiment, due to large coupling losses, and at the same time so as to broaden the spectra as wide as possible, we use NL-PCF with 4.5 μm MFD and length of 13 cm for generation research of wideband tunable femtosecond laser pulses.

Figures 3(a)–3(h) respectively present the broadened output spectra exited from the utilized 13 cm-long NL-PCF. The output power from NL-PCF is also respectively labeled in the upper right corner of each spectra distribution. Under the maximum 3.2 W incident power, 1.23 W coupled output power can be obtained behind NL-PCF. As shown in Figs. 3(a)–3(d), for the relatively low coupled power case, the spectra broadening is not prominent. However, as the coupled power exceeds 500 mW, the spectra exited from NL-PCF significantly broaden with the increment of power. For 1.23 W coupled output power, the left-most and right-most spectral lobes are respectively shifted to 816 nm and 1300 nm. However, as the femtosecond laser propagates along NL-PCF, due to the coupling losses, dispersion, etc., the nonlinear effects induced spectra broadening are relatively weak in comparison with the quasi-linear propagation part in PCF. As a result, only a very small fraction of the incident power can convert into new wavelength region, and most of the power still stays in the original input wavelength. Therefore, as shown in Fig. 3, the relative intensity of the newly generated spectra components is low compared with that of the input wavelength. In experiment, we find that wider incident pulse spectra are not beneficial for improving conversion efficiency of the new wavelength spectra components. As shown in Fig. 3, only center parts of the incident spectra decrease in amplitude. The edge parts have no apparently changes during the propagation in NL-PCF. Therefore, we conclude that by reasonably optimizing the mode-locked spectrum, obtaining high density spectra distribution, and simultaneously reducing the repetition rate under the comparable power output condition, the new spectra components will increase in amplitude.

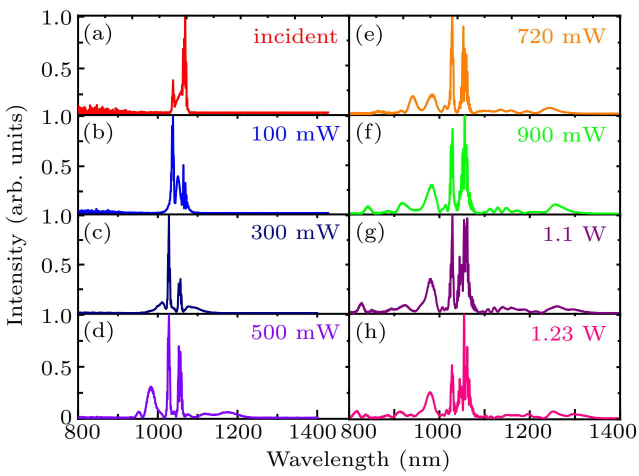

Fig. 3. Output spectra corresponding to different coupled output power.

In experiment, we selectively filter the representative spectra lobes from the nonlinear broadening spectra using the SFs with different center wavelengths and spectral bandwidths. The filtered spectra are respectively centered at 902.1 nm, 923 nm, 950.7 nm, 971.9 nm, 998.9 nm, 1100 nm, 1151.2 nm, 1198.6 nm, 1251.6 nm, and 1290.1 nm, which are all colored shown in Fig. 4.

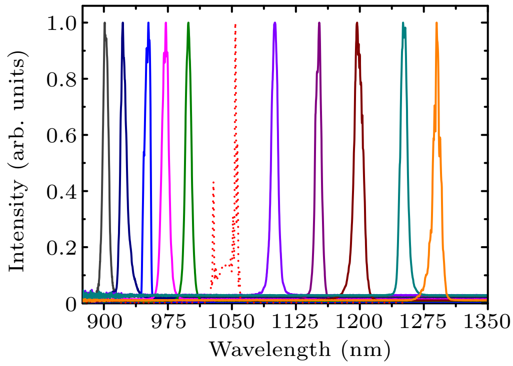

Fig. 4. Tunable spectra output from the presented wideband tunable femtosecond source. The red dashed line shows the incident spectra.

Figure 5 shows the available maximum average power for different central wavelengths. Both central wavelength and average power are measured after the spectral filtering. As shown, the average power is relatively low at different central wavelengths. For example, at 1290.1 nm, the average power is 6 mW. The corresponding energy conversion efficiency is estimated to be 0.48%. Further power increment is feasible by adopting SFs with high transmission efficiency and width transmission bandwidths. In addition, by re-shaping beam spot of the incident laser and optimizing parameters of NL-PCF and coupling lens, the nonlinear energy conversion efficiency can be potentially promoted.

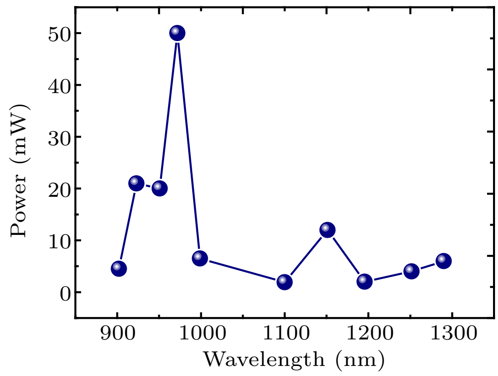

Fig. 5. Available maximum average power for different central wavelengths.

For laser pulses centered at 902.1 nm, 923 nm, 950.7 nm, 971.9 nm, 998.9 nm, and 1100 nm, the measured pulse widths are respectively 165 fs, 167 fs, 169 fs, 206 fs, 202 fs, and 221 fs assuming Gauss fitting. Figure 6 shows the intensity autocorrelation traces corresponding to different central wavelengths. In addition, the temporal widths for the pulses with central wavelengths beyond 1150 nm cannot be measured due to the limited measureable wavelength range of our available intensity auto-correlator.

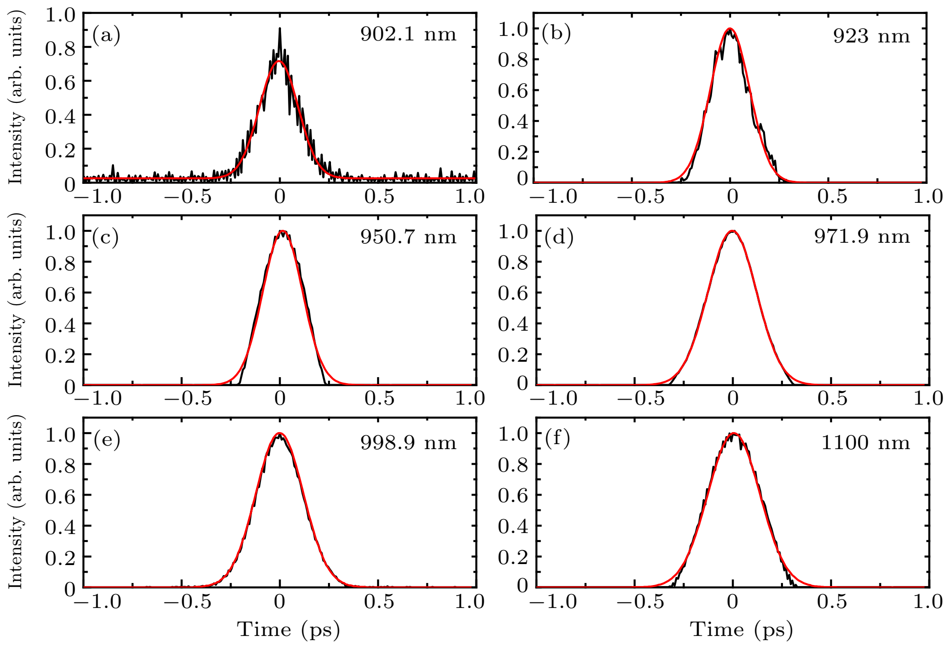

Fig. 6. Intensity autocorrelation traces corresponding to different central wavelengths. The colored red lines represent Gauss fitting.

4. Conclusion

In this paper, we present a simplified configuration used for generating wideband tunable femtosecond laser output based on our home-made compact and cost-benefit high-average-power fiber oscillator as the pump source. By experimentally optimizing the structure parameters of NL-PCF and the power of the incident pulses, wideband tunable femtosecond laser output with tuning range of 390 nm has been obtained. Although the measured new wavelength femtosecond laser has low output power, we believe the research method is worth considering and should be explored by the researchers in this field. Moreover, by optimizing spectra of the incident pulses, reducing the repetition rate of mode locking, and optimizing the parameters of NL-PCF and coupling lens, the power conversion efficiency for the femtosecond laser with wavelength out of traditional laser gain media can be further improved.

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