Red-green-blue (RGB) light generator using tapered fiber pumped with a frequency-doubled Yb-fiber laser

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Abstract: We report on successful realization of a picosecond visible-continuum source embedding a single mode fiber taper. The output of ytterbium mode-locked fiber laser was frequency doubled in a periodically-polled lithium niobate (PPLN) crystal to produce green pump light. Spectral brightness of the white light generated in the tapered fiber was improved by limiting the broadening just to the visible wavelengths. The influence of taper parameters, particularly the dispersion, on white light spectrum has been studied.

OCIS codes: (190.4370) Nonlinear optics, fibers; (190.2620) Frequency conversion; (140.3510) Lasers, fiber; (320.7090) Ultrafast lasers; (130.3730) Integrated optics: Lithium niobate

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1. Introduction

Supercontinuum radiation (SC) has received remarkable attention since its early demonstration [1]. Despite complex interplay of nonlinear effects involved in the spectral broadening, supercontinuum radiation has been soon recognized as a useful tool for metrology [2], life sciences [3], the generation of ultrashort pulses [4], optical telecommunications [5]. Owing to their impressive spectral brightness, the SC sources represent an attractive alternative to traditional broadband (incandescent or fluorescent) light sources. Since the first demonstration of broadband light generation in guided media [6], SC sources based on improved nonlinear converters have become much more than just a subject for academic research. With the advent of powerful laser sources, ultra-broadband supercontinua exploiting different nonlinear media including photonic crystal fibers (PCF) [7] and fiber tapers [8] have been demonstrated.

Many applications require high-brightness RGB light sources with little energy outside the visible range. Traditional broadband sources fail to comply with these requirements, since typical "white-light" spectrum extends either in ultra-violet (e.g. with fluorescent emitters) or infrared (e.g. with incandescent sources) range. A supercontinuum source producing only visible light is a challenging task, since most supercontinuum sources nowadays use mode-locked infrared solid-state or fiber lasers. Using infrared lasers as a pump source to generate a visible continuum tends to be inefficient because significant fraction of the pump power is transferred to the far infrared, as expected from the SC formation mechanism [9]. A large amount of the pump energy is lost thus decreasing an overall efficiency of the RGB white-light source.

The visible light sources based on nonlinear frequency conversion with the spectrum broadening limited to RGB range would efficiently convert the pump power into visible light, providing better spectral brightness and wall-plug efficiency than the sources based on infrared-pump supercontinua. Since SC radiation is generated nearly symmetrically around the pump wavelength, the rational solution for visible light generation is to employ a pump laser whose wavelength is situated in the middle of the visible range around 530 nm.

Continuous improvement in nonlinear crystals has made a frequency conversion in periodically-polled crystals a practical technique to produce visible light from infrared lasers. Particularly, ytterbium fiber mode-locked lasers operating around 1060 nm and used together with nonlinear crystals optimized for frequency-doubling are a very promising source of visible pump pulses at 530 nm [10].

Another crucial issue in supercontinuum generation is the dispersion characteristic of the nonlinear medium. To achieve an efficient pump conversion to SC, the pump wavelength should match the zero dispersion wavelength (ZDW) of the nonlinear medium. The visible SC generators would thus require nonlinear media with zero-dispersion at visible wavelengths. PCF and fiber tapers can be engineered to have a ZDW around 530 nm. Notable results in broadband supercontinuum generation within both PCF and fiber tapers pumped with green light have been reported [11-12]. However, the spectral brightness of visible radiation and conversion efficiency are still to be improved by further optimization of the SC generator.

Fiber lasers have strong potential for the systems, where long term stability and maintenance-free operation are required. Semiconductor saturable absorber mirror (SESAM) based mode-locked fiber lasers are well known for their excellent pulse quality, small footprint and unprecedented reliability [13]. Mode-locked fiber lasers can produce ultrashort pulses with high peak power representing nearly ideal pump source for supercontinuum generation.

In this paper, we report on a high brightness, all-visible supercontinuum source using pump signal from mode-locked ytterbium fiber laser frequency-doubled in a periodically-poled lithium niobate (PPLN) crystal. White light radiation is then generated in a purposely-designed tapered fiber. An attractive feature of the tapered fiber important for practical SC sources is that ZDW could be easily adjusted by controlling the pulling conditions. We investigate the effect of taper ZDW and input power on a spectral bandwidth and shape of visible continuum. The results of this study show the tolerances of taper parameters that allow for efficient spectral broadening.

2. Experimental setup

The experimental setup used for supercontinuum generation is shown in Fig. 1.

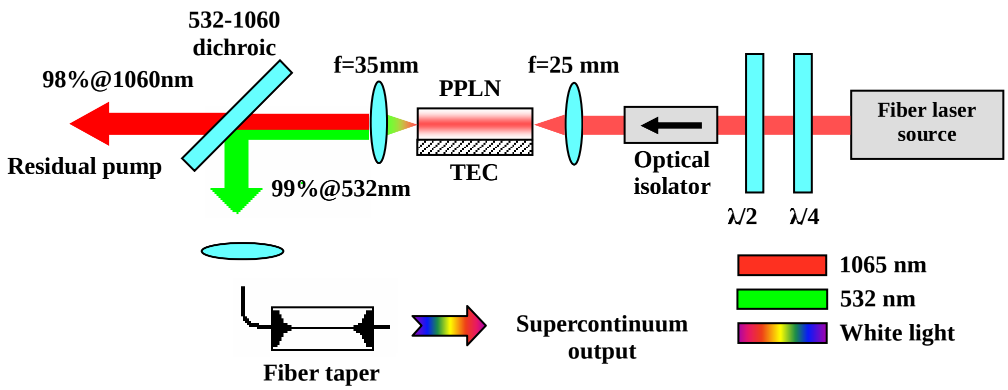

Fig. 1. Experimental setup for white light generation in tapered fibers: PPLN – periodically-poled lithium niobate; TEC – thermo-electric cooler.

The pump source is an Yb-doped fiber laser mode-locked by a SESAM. A double-clad Yb-fiber amplifier is used to boost the average power up to 2 W. The laser spectrum taken at full power with the center emission wavelength of 1064 nm is shown in Fig. 2(a). The pulse autocorrelation trace revealing a pump pulse width of 3 ps is shown as an inset. The pump laser beam passes through polarization correction waveplates and an optical isolator which eliminates back reflections preventing the changes in the power and spectrum of the system. Owing to random polarization of the pump beam, the polarization-dependent optical isolator limits the usable pump power to ~1 W.

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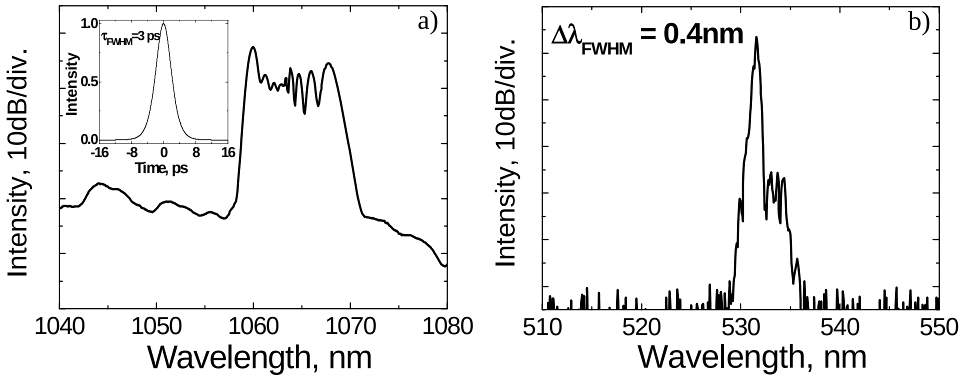

Fig. 2. Pump spectrum and autocorrelation shown as an inset (a) and corresponding spectrum of the second-harmonic (SH) radiation.

The nonlinear crystal used for frequency conversion was a 500 µm-long PPLN made by Stratophase Ltd. The PPLN grating structure was formed using standard photolithography. The domain inversion was performed in the z-axis at room temperature with a single high-voltage pulse of ~11 kV applied through liquid electrodes. A set of gratings with periods of 6.50, 6.54 and 6.58 µm was fabricated. In these experiments, best results have been obtained with 6.58-µm period grating operated at 160°C [14] which ensures optimum phase matching with our pump source with the wavelength centered at 1064 nm. The crystal was placed inside an electrical oven controlled by a digital feedback loop that allows to control the crystal temperature with a precision of 0.1°C. Additionally, high operating temperature eliminates any potential problems caused by the photorefractive effect. The pump light was focused onto the crystal using the lens with a focal length of 25 mm. At the highest pump power, we obtained ~120 mW of SH power, corresponding to a conversion efficiency of about 14%. The pump and SH radiation emerging from the crystal were combined using a lens with 35-mm focal distance and broadband antireflection coating. The SH light was then separated from residual pump radiation by a dichroic mirror exhibiting 99% reflectivity for the SH light and 98% transmission for the residual pump. The SH light was subsequently launched by a microscope objective into the pigtail of the fiber with a tapered segment. The maximum SH power coupled to the 8-µm core fiber pigtail was 80 mW. The spectrum of the SH light measured at full power is presented in Fig. 2(b). The spectral bandwidth of the SH radiation is 0.4 nm and it approximately matches the bandwidth of the PPLN crystal.

3. Fiber tapers

The fiber tapers studied in this experiment were fabricated using a home-made fiber tapering workstation. We use commercial SMF-28 fiber as primary material, because of its excellent diameter uniformity. During tapering, the fiber was heated by two hydrogen-oxygen burners equipped with separate gas flow controllers. The fiber through-put during tapering was monitored by launching a low power 532-nm signal into the input pigtail and reading the transmitted power continuously. The tapering rig is fully computer controlled, which enables us to build tapers with accurately adjusted length and diameter of the waist. To ensure low loss adiabatic tapers, we used a double-stage tapering strategy. First, the fiber is pulled under a fixed heated zone until the waist diameter reaches ~10 µm. Then the heated zone size increases linearly with progressive pulling of the fiber [15] until the target waist diameter is reached. To obtain consistent results, the computer program keeps the waist length constant for all tapers studied despite their waist diameter by controlling the amount of molten glass at the initial tapering stage. After pulling, the tapers are packaged in a plastic case and characterized. The taper waist diameter has been accurately measured using images taken by a high resolution CCD camera through a large magnification optical system (150X). Image

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analysis software was employed to determine the waist diameter with 0.05-µm accuracy. A typical bi-conical profile is presented in Fig. 3 showing a uniform waist with length of 19 cm for the taper with total length of 26 cm.

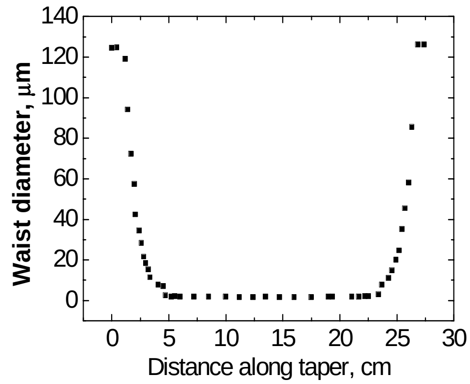

Fig. 3. Sample taper profile.

4. Experimental results

The potential of the tapered structures with different waist diameters to supercontinuum generation has been first examined by studying their chromatic dispersion at pump wavelength. It has been shown that the optical field during the propagation along the down-taper transition in a fiber detaches from the fiber core and penetrates into the cladding, becoming eventually guided by the glass-air interface [16]. The taper waist has been modeled with a circular strand of glass surrounded by air. This approximation is valid for structures used in SC experiments since tapering ratio exceeds 10^2 and therefore the fiber core becomes insignificantly small and cannot support the guided modes. Because our tapered transitions (conical sections of the structure) are short compared to the length of the waist, as seen from Fig. 3, we neglect the influence of the conical sections of the taper. The chromatic dispersion was evaluated by solving the propagation constant eigenvalue equation for a given waist diameter [17]. The chromatic dispersion at 531 nm for various diameters of the waist is given in Fig. 4.

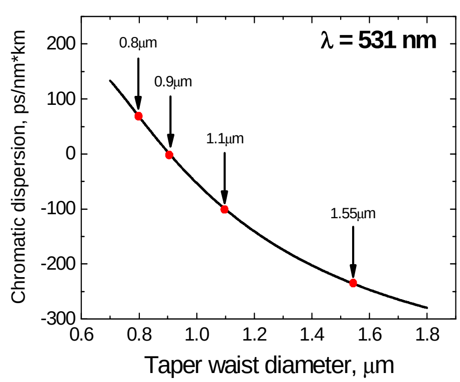

Fig. 4. Chromatic dispersion versus taper waist diameters for λ=531 nm. Waist diameters of tested tapers are indicated with arrows.

Figure 4 indicates that the optimum supercontinuum efficiency can be achieved with a 0.9-µm waist taper, whose zero dispersion wavelength matches the pump wavelength of 531 nm. The influence of taper parameters on SC efficiency was studied by varying the waist diameter. Particularly, it was confirmed that minor change in waist diameter (0.1 µm) affects drastically the SC efficiency. The dispersion characteristics of studied tapers are shown in Fig. 5.

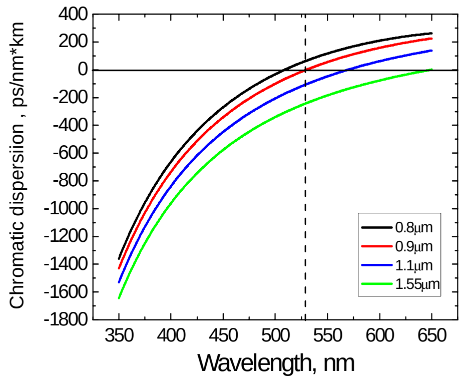

Fig. 5. Chromatic dispersion of tapered fibers with different parameters. The legend shows the taper waist diameters; the dashed line indicates the pump wavelength (531 nm).

With a fiber pulling workstation available for these experiments, the ZDWs of the tapers could be accurately adjusted during taper fabrication to match desired pump wavelength. All tapers used in this study have losses below 0.09 dB/cm at the pump wavelength.

After taper characterization, the output from PPLN crystal was coupled to the taper using objective lens. Strong nonlinear conversion to SC within the taper with the diameter of the waist of 0.9 µm providing optimal dispersion characteristics results in a radiation covering the entire visible wavelength range. The optical spectra of the visible continuum measured for different pump powers are shown in Fig. 6(a). Figure 6(b) illustrates the SC radiation after reflection from diffraction grating.

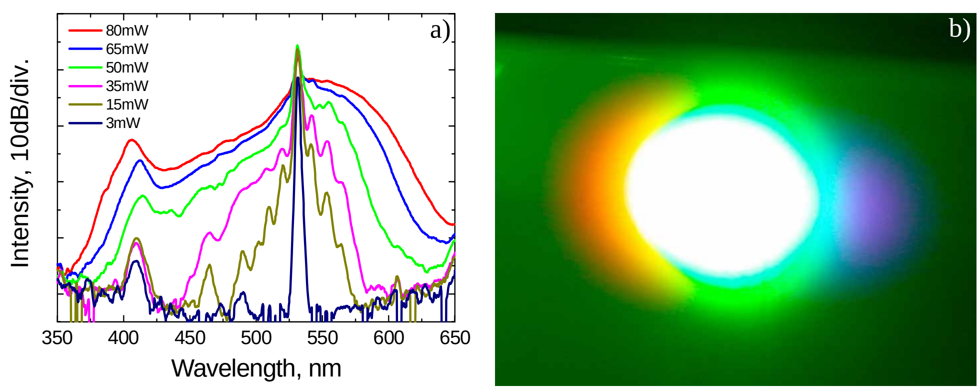

Fig. 6. Visible white light continuum at various input power levels (a) and supercontinuum spectrum photograph (b) for the taper with waist diameter of 0.9 µm.

From Fig. 6 it can be seen that the supercontinuum energy is limited to the visible wavelength range, without significant UV or IR components. At maximum pump power, the average power of supercontinuum radiation reaches ~55 mW corresponding to a spectral brightness of 0.17 mW/nm.

The effect of the ZDW on SC efficiency was then studied using tapers with different waist diameters. The SC spectra from the tapers measured at different input powers are presented in Fig. 7(a-c).

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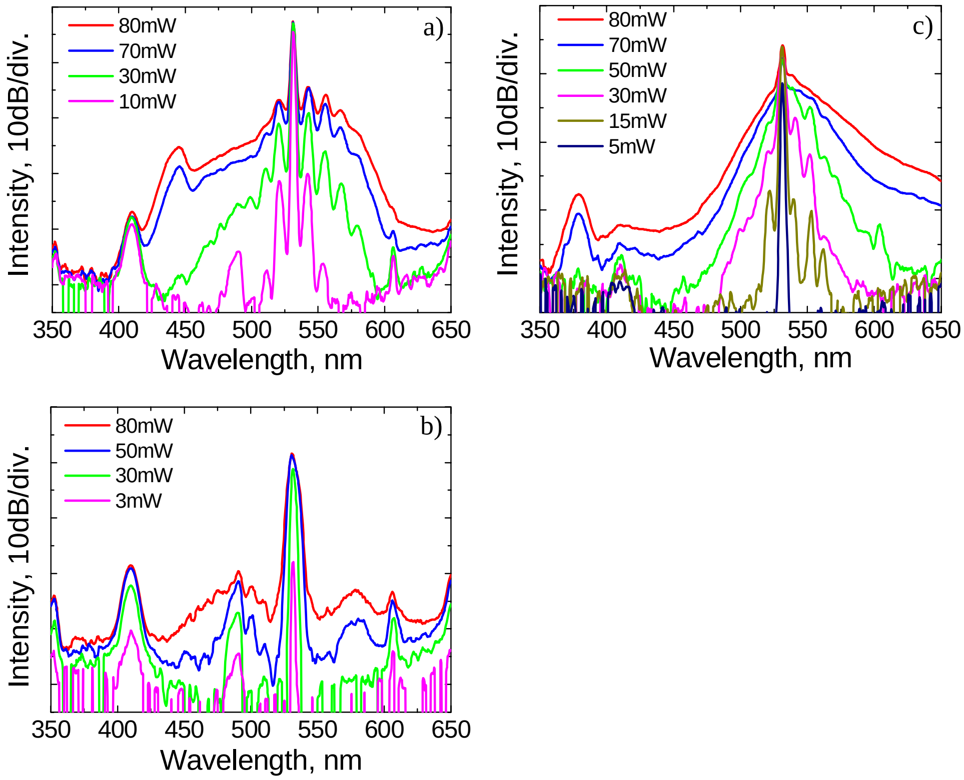

Fig. 7. Visible continua obtained in tapers with waist diameter of 1.1 µm (a), 1.55 µm (b), and 0.8 µm (c) with pump power as a parameter.

It can be seen that small variations in waist diameter result in a large change of the SC spectrum revealing an important role played by chromatic dispersion. The supercontinuum spectrum with improved bandwidth and flatness has been obtained from the taper with a zero dispersion wavelength closest to the pump wavelength. Increasing the taper waist diameter over the optimal value of 0.9 µm causes the pump pulse to propagate in normal dispersion regime which, combined with decreased nonlinearity due to larger waist cross-section, leads to lower supercontinuum generation efficiency, as seen from Fig. 7(a). Ultimately, a taper with a 1.55-µm diameter waist has too large normal dispersion and too low nonlinearity to generate significant spectral broadening, as seen in Fig. 7(b).

Using a taper with diameter only slightly smaller (~0.1 µm) than the optimal value leads to poor SC efficiency, as seen in Fig. 7(c). This effect can be understood from soliton fission theory of supercontinuum generation [9, 18]. As the taper waist diameter decreases, the pump pulse experiences higher anomalous dispersion. Consequently, the pump pulse is converted into a lower order soliton [9], despite a higher light density in the taper with decreased diameter of the waist. As a result, upon the breakup, the pump pulse generates lower number of fundamental solitons and hence the non-soliton blue-shifted radiation is also strongly reduced, as clearly seen from Fig. 7(c). In a contrary, the amount of red-shifted radiation increases as a result of enhanced Raman shifting and self-phase modulation owing to higher optical field intensity within the taper with the reduced waist diameter.

The results in Fig. 7 indicate that the tolerances for the taper waist required for efficient SC generation are very tight. A deviation of only 0.2 µm from the optimal waist diameter, that ensures the zero dispersion at the pump wavelength, can dramatically change the supercontinuum spectral shape. This conclusion is supported by the data shown in Fig. 4,

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which indicates that the large change in chromatic dispersion is expected even for small variations in the taper waist diameter.

5. Conclusion

We have demonstrated visible white-light generation using tapered fiber with engineered dispersion profile. Pump light was provided by a mode-locked ytterbium fiber laser frequency-doubled in a PPLN nonlinear crystal. An optimal taper diameter for supercontinuum generation was identified based on numerical simulations and measurements. The brightness of the source with the bandwidth covering entire visible spectral range is enhanced by limiting the spectral broadening in a tapered fiber to the visible wavelengths. The influence of taper parameters on the white light generation has been studied.

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