Broadband wavelength conversion in a germanosilicate-core photonic crystal fiber

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A photonic crystal fiber with a germanosilicate core having a nonlinear coefficient of 40 $(\mathrm{W\,km})^{-1}$ near the single dispersion zero at 1.09 μm is fabricated and studied. Broadband parametric wavelength conversion of the Ti:sapphire laser output tunable at 0.8 μm to the 1.55 μm band is obtained at 1.064 μm cw pump. The tuning of the converted signal in the 300 nm range was first realized without variation of the pump wavelength. © 2009 Optical Society of America

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Rapid development of information technology demands increasing the bandwidth of fiber-optic communication systems. Efficient wavelength conversion between telecommunication bands at 0.8 and at 1.3 or 1.55 μm would allow these transparency windows to be more fully utilized in a fiber network. Parametric wavelength converter based on four-wave mixing (FWM) in a silica photonic crystal fiber (PCF) is very promising for information exchange between these widely separated transparency windows. The FWM wavelength conversion can be realized in a one-step process and at lower pump powers in comparison with a Raman converter. Nevertheless, there are two specific requirements for fibers designed to translate signals between telecommunication windows through FWM. The first one follows from the fact that parametric process is efficient only at phase matching ($\Delta k=\beta_a+\beta_s-2\beta_p+2\gamma P=0$, where Δk is the phase mismatch; β_a, β_s, and β_p are the propagation constants of the anti-Stokes, the Stokes, and the pump waves, respectively; $\gamma=2\pi n_2/\lambda A_{\mathrm{eff}}$; n_2 is the nonlinear refractive index; λ is the wavelength; A_{eff} is the effective mode area; and P is the pump power). For large Stokes shifts having a narrow gain bandwidth (0.01–0.1 nm), phase matching is difficult to achieve even in a 1-m-long fiber because of inherent longitudinal variations of fiber parameters [1,2]. Therefore, the fiber should be highly nonlinear in order to obtain a nonlinear amplification length $L_a=1/\gamma P$ less than a coherence length $L_c=\pi/\Delta k$. Moreover, the most favorable case for FWM conversion with large Stokes shifts in single-mode fibers takes place when the pump wavelength has a small (tens of nanometers) offset to the positive dispersion side from a zero dispersion wavelength (ZDW) [3]. Only in this case there is no loss of pump energy on additional FWM radiation with phase-matched small Stokes shifts [4]. The pump wavelength should be in a region of 1.0–1.1 μm in accordance with the energy law ($2\omega_p=\omega_a+\omega_s$, where ω_p, ω_a, and ω_s are the pump, anti-Stokes, and Stokes frequencies, respectively) for a parametric process with the anti-Stokes in a region of 0.8 μm and the Stokes in a region of 1.3 or 1.55 μm. Therefore, the fiber should have the dispersion characteristic with the ZDW in the 1 μm region too.

Because of the large core–cladding difference, low-loss silica PCFs with a large fill factor f ($f=(\pi/2\sqrt{3})d^2/\Lambda^2$, where d is the hole diameter, and Λ is the pitch) are the best suited for obtaining a high nonlinear coefficient γ. However, the ZDW in these fibers can be changed only through scaling (a proportional change of d and Λ with f=const). As a result the value of γ becomes moderate at displacement of the ZDW from the short wavelength region ($\lambda_0=0.6$–0.8 μm), where A_{eff} has the smallest value of 1–4 $\mu\mathrm{m}^2$ to the 1 μm region [4–10]. Current results on conversion efficiency G [$G=P_{s,a}(L)/P_{a,s}(0)$, where $P_{s,a}(L)$ is the Stokes (anti-Stokes) converted signal power at the fiber output and $P_{a,s}(0)$ is the anti-Stokes (Stokes) signal power at the fiber input] obtained by experimentalists for FWM with large Stokes shifts correlate with the value of γ at the ZDW. The authors of [4] used a PCF with $\gamma=95$ $(\mathrm{W\,km})^{-1}$ near the ZDW at 750 nm to obtain 1493–518 nm FWM conversion with an efficiency of 0.3% with 200 mW of cw pump power. In our previous work [7], we obtained a 0.1% efficiency for 1.098–0.687 μm conversion in a silica PCF with $\gamma=30$ $(\mathrm{W\,km})^{-1}$ near the ZDW at 0.85 μm with cw pump power of 100 mW and only 5×10^{-4}% efficiency for 845–1569 nm conversion in a fiber with the ZDW at 1.129 μm ($\gamma=4$ $(\mathrm{W\,km})^{-1}$) with cw pump power of 600 mW.

The GeO_2 dopant in a silica core is known to enhance nonlinearity and to shift the ZDW to longer wavelengths [9,10]. According to the numerical analysis given in [9] for the silica PCF with a core heavily doped with GeO_2, it is possible to obtain the effective mode area by 1 order of magnitude less than that in a pure-silica PCF at the ZDW in a 1 μm region.

In this work we realized experimentally a design for a two-ring PCF with a germanosilicate core considered numerically in [9]. The broadband parametric conversion of the Ti:sapphire laser output tunable at 0.8 μm to the region of 1.55 μm was obtained in the fabricated fiber by a cw Nd:YAG pump at 1.064 μm.

The PCF with a germanosilicate core was fabricated in two stages. At first, a preform having 24 mol.% GeO_2 in the core was made by the modified chemical-vapor deposition method. The core profile is shown in Fig. 1(a). Then, the preform cross-section was increased by jacketing, and two rings of holes in hexagonal symmetry were made by drilling. Figure 1(b) shows the cross section of the fiber drawn from this preform. The fiber had a diameter of the doped core region of 1.7 μm. The hole diameter and the pitch were 2.7 and 3.1 μm, respectively (f=0.69). The variations of the outer diameter along the fiber measured during drawing were ~2.5% [Fig. 1(c)]. The loss was measured to be 20–30 dB/km in the 0.8, 1.3, and 1.55 μm bands [Fig. 1(d)].

Figure 2 shows the dispersion characteristics calculated using the Matlab-Femlab package for fibers with the same geometry of holes as in the prepared fiber. Curve 1 calculated for a fiber with the core profile of Fig. 1 has the ZDW at 1.09 μm. Curve 2 was calculated for a steplike profile in order to evaluate the influence of the core profiles on dispersion. The noticeable shift of the ZDW between these curves (46 nm) shows that this parameter should be taken into account in designing the PCF. Curve 3 calculated for a pure-silica core was given in Fig. 2 for comparison. The curve demonstrates a strong shift to the shortwave band with the ZDW at 0.91 μm for this geometry of holes. The dependence of the phase-matched Stokes–anti-Stokes pair on the pump wavelength shown in the inset of Fig. 2 was calculated for the prepared fiber using the dispersion curve 1. For a pump at 1.064 μm, the phase matching has the anti-Stokes at 0.81 μm and the Stokes at 1.54 μm; therefore, this fiber can be used for wavelength conversion between these telecommunication bands. The effective mode area was calculated to be 4.4 μm^2 (γ=40 $(W\,km)^{-1}$) at the pump wavelength of 1.064 μm.

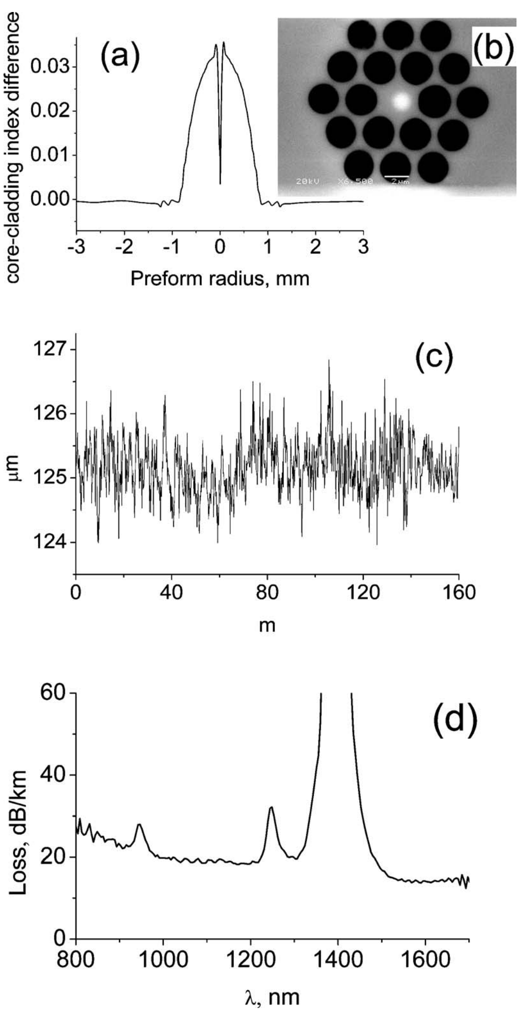

Fig. 1. (a) Profile of a germanosilicate core measured in a fiber preform, (b) scanning electron micrograph of the fiber cross-section, (c) diameter variations measured during drawing, (d) loss measured in a microstructure fiber with a germanosilicate core. The maximal value of the OH peak at 1.4 μm is 260 dB/km.

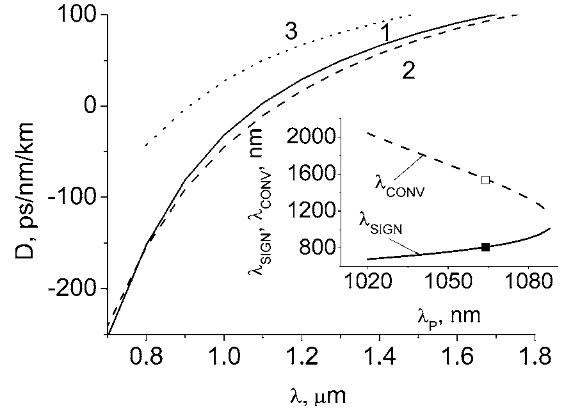

Fig. 2. Dispersion calculated for fibers having the same geometry of holes (Λ=3.1 μm, d/Λ=0.86) and different cores. 1, doped core with a profile identical to that for the fiber under study (Fig. 1) 2, the same doped core with a step-index profile; 3, undoped SiO_2 core. Inset, phase-matched wavelengths λ_{SIGN} (anti-Stokes) and λ_{CONV} (Stokes) as functions of the pump wavelength λ_P calculated from dispersion curve 1. The squares are experimental values obtained for the pump at 1.064 μm.

Using the well-known relations for FWM efficiency [10], we evaluated that 22 m of our fiber would be enough for a 0.8–1.55 μm conversion without a loss in signal power (G=1) at a pump power of 1 W and constant fiber parameters. However, as follows from Fig. 1(c), our fiber had diameter variations with a short period of less than 1 m. The 2.5% variations of the fiber diameter lead to the displacement of the ZDW within the 20 nm range and, as a consequence, to a decrease of the coherence length. On the other hand, these variations produce a positive effect, significantly broadening the parametric amplification band. Numerical analysis was conducted for a PCF with 2.5% diameter variations to show that the phase matching was possible for the converted signal in the tuning range of 250 nm.

Parametric conversion was studied using a cw Nd:YAG laser as a pump at 1.064 μm and a cw Ti:sapphire laser tunable in the region of 0.75–0.87 μm as a signal source. The Nd:YAG laser had a linewidth of 0.04 nm. The Ti:sapphire laser with a 0.08 nm linewidth was pumped by a solid-state cw green laser (Spectra Physics, Millenia) and had a three-plate Lyot filter inside the cavity for wavelength tuning. A telescope and a 40× objective were used to inject both radiations into the fiber. The pump power was 500–900 mW, and the signal power was 1–10 mW at the fiber output. The measurements were performed with different fiber lengths up to 200 m. The converted signal with a maximal amplitude at 1540 nm was registered with an optical spectrum analyzer, when the Ti:sapphire laser output was tuned to 813 nm in good agreement with the calculated value (Fig. 2). At small lengths ($\leqslant$20 m) the conversion efficiency G was −50 dB, and the tuning range for the converted signal with a signal-to-noise ratio of more than 10 dB was $\leqslant$30 nm. The conversion efficiency was increased with increasing fiber length, reaching the maximal value $G=-30$ dB with a 200-m-long fiber. According to our estimates, this conversion efficiency corresponds to a coherence length of only 80 cm. We observed a significant broadening of the tuning range up to 300 nm with increasing fiber length to 200 m. In a 200-m-long fiber, we tuned the converted signal wavelength from 1672 to 1372 nm with the lowest conversion efficiency level of −50 dB by tuning the signal wavelengths from 780 to 869 nm (Fig. 3). The linewidth of the converted signal was within 0.1 nm over all the tuning range. The fact that a tuning range of 300 nm

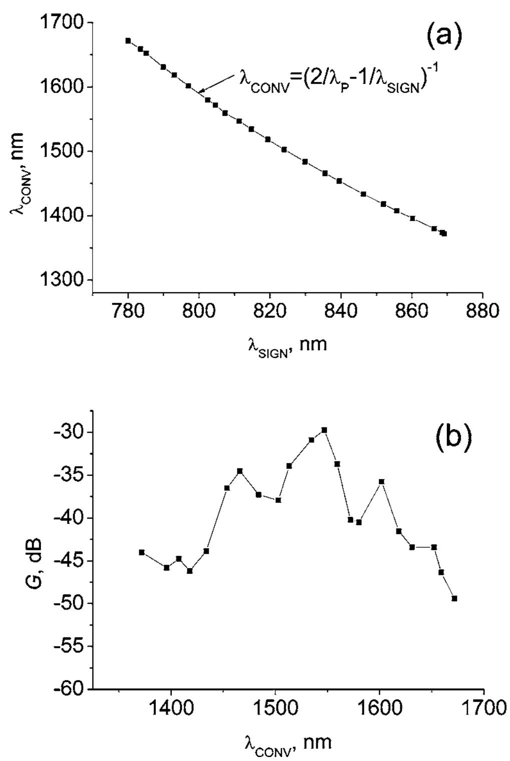

Fig. 3. (a) Measured wavelength of the converted signal λ_{CONV} versus the signal wavelength λ_{SIGN} (squares) and Stokes–anti-Stokes wavelength dependence for the FWM process (line). (b) Conversion efficiency as a function of the converted wavelength. The fiber length is 200 m. The pump wavelength is 1.064 μm.

for the converted signal, close to theoretical estimates, was obtained only at the fiber length of 200 m can be explained by the stochastic character of diameter variations. The amplification length is different for different detuning of the diameter from the weighted average value, reaching maximum at large fiber lengths. This results also in modulation of the wavelength dependence of the conversion efficiency G, which can be seen in Fig. 3(b).

Further development of this tuning method should include minimization of the stochastic nature and optimization of diameter variations for obtaining the maximal amplification lengths. It is worth noting that in the case of multichannel FWM generation, the tuning method using the variations of fiber diameter allows signal translation simultaneously on all channels and has an advantage in comparison with the usual method of tunable pump wavelength [5]. For a tunable pump, the rate of multichannel data exchange would be limited by the pump tuning rate.

In conclusion, we have studied a PCF with a heavily doped germanosilicate core fabricated with the aim to enhance the efficiency of the parametric conversion between telecommunication bands of 0.8 μm and 1.55 μm. The PCF with a technologically simple design of two rings of holes in hexagonal symmetry had, to our knowledge, the highest nonlinear coefficient of 40 $(\mathrm{W\,km})^{-1}$ for the dispersion characteristic with a single ZDW in a 1 μm wavelength region. Parametric wavelength conversion of 0.8–1.55 μm with efficiency of 0.1% was obtained in this fiber at cw pump powers of 500 mW at the fiber output. The tuning of the converted signal in the 300 nm band, overlapping the S, C, and L bands of telecommunication window at 1.55 μm, was first realized owing to unique combination of the high nonlinearity and diameter variations of the fiber. This result opens the way to multichannel data exchange throughout telecommunication windows.

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