Computational study of 3–5 μm source created by using supercontinuum generation in As_2S_3 chalcogenide fibers with a pump at 2 μm

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Received June 8, 2010; revised August 2, 2010; accepted August 5, 2010;
posted August 6, 2010 (Doc. ID 127158); published August 23, 2010

We present simulation results for supercontinuum generation using As_2S_3 chalcogenide photonic crystal fibers. We found that more than 25% of input power can be shifted into the region between 3 μm and 5 μm using a pump wavelength of 2 μm with a peak power of 1 kW and an FWHM of 500 fs. The broad dispersion profile and high nonlinearity in As_2S_3 chalcogenide glass are essential for this application.

OCIS codes: 060.2280, 060.2390, 320.6629.

Generating light in the mid-IR region has drawn much attention recently. This light can be used for a wide variety of military, medical, and sensing applications [1]. Supercontinuum generation uses the Kerr and Raman effects in optical fibers to broaden the bandwidth of an optical signal [2]. It could also potentially generate light in the mid-IR region. Price *et al.* [3] have demonstrated theoretically that it is possible to generate a mid-IR supercontinuum from 2 to 5 μm using a bismuth glass photonic crystal fiber (PCF). Domachuk *et al.* [4] have experimentally generated a mid-IR supercontinuum with a spectral range of 0.8 to 4.9 μm using a tellurite PCF. However, the amount of power generated in the wavelength range between 3 μm and 5 μm using a pump source at a wavelength of 2 μm is less than 5% [3]. A pump wavelength of 2 μm is important because fiber lasers can generate wavelengths up to 2 μm with a peak power of 5 kW and are thus a good source of supercontinuum generation [5].

Prior work has been done using chalcogenide waveguides or fibers to generate a supercontinuum at wavelengths below 2 μm [6–9]. In this Letter, we show that more than 25% of the input power can be shifted into the region between 3 μm and 5 μm using a As_2S_3 chalcogenide PCF with an input wavelength of 2 μm and an input peak power of 1 kW. The principal mechanisms that generate a supercontinuum are soliton fission and the soliton self-frequency shift. The strength of the nonlinearity and the breadth of the anomalous dispersion regime both contribute to the relatively large amount of power that can be obtained between 3 μm and 5 μm. The nonlinear refractive index of As_2S_3 chalcogenide glass is 1 order higher than that of bismuth glass [3]. The anomalous dispersion regime for As_2S_3 chalcogenide PCF can extend from 2 μm to 6 μm, while Fig. 5 in [3] shows that the anomalous dispersion regime ranges from 1.5 μm to 3 μm in bismuth glass fiber, so that it is only possible to generate a small amount of power in the wavelength region between 3 μm and 5 μm. Tellurite glass has a high loss above 3 μm [4]. Both As_2Se_3 and As_2S_3 chalcogenide glass have low loss in the mid-IR region [10], but they have different material dispersions. The material zero-dispersion wavelength (ZDW) for As_2S_3 is lower than the material ZDW for As_2Se_3 [11]. At a wavelength of 2 μm, As_2S_3 PCFs have anomalous dispersion, while As_2Se_3 PCFs have normal dispersion. Hence, one would expect to generate a much wider supercontinuum by using an As_2S_3 PCF with a pump wavelength of 2 μm in the anomalous dispersion region [2].

In a prior work, we maximized the bandwidth that can be obtained using supercontinuum generation in an As_2Se_3 chalcogenide PCF with a pump that uses an optical parametric amplifier at a wavelength of 2.5 μm [11]. We showed that one can generate more than 4 μm of a relatively flat spectrum using four-wave mixing in a combination of self-phase modulation and the soliton self-frequency shift [11]. In this Letter, instead of aiming for a wide spectrum, we want to generate a light source in the range between 3 μm and 5 μm using a fiber laser of 2 μm. In a prior brief meeting report, we showed that more than 25% of the input power can be shifted into the region between 3 μm and 5 μm [12]. In this Letter we give, for the first time (to our knowledge), a detailed prescription for maximizing the power in the region between 3 μm and 5 μm using an As_2S_3 chalcogenide PCF, including the dependence on the input power.

We model the light generation between 3 μm and 5 μm in two stages. Our goal is to find an optimized pitch of PCF that maximizes the power between 3 μm and 5 μm. We set the ratio of the hole diameter to pitch, d/Λ, to 0.4, so that the fiber is single mode [11,13].

In the first stage, we determine the chromatic dispersion in the fiber, given the material dispersion and PCF geometry. The refractive index of the As_2S_3 chalcogenide glass was measured at the Naval Research Laboratory by ellipsometry [14]. The PCF has five layers of air holes in a hexagonal structure. We calculated the effective index using COMSOL Multiphysics, a commercial full-vector mode solver based on the finite-element method. We then used the effective index to calculate the total dispersion, which includes waveguide dispersion and material dispersion. Figure 1 shows the total dispersion versus wavelength with a pitch of 2 μm, 3 μm, and 4 μm.

In the second stage, we solve the generalized nonlinear Schrödinger equation described in [11]. The model used in this Letter is the same as in [11], except that the nonlinear refractive index, the dispersion versus wavelength,

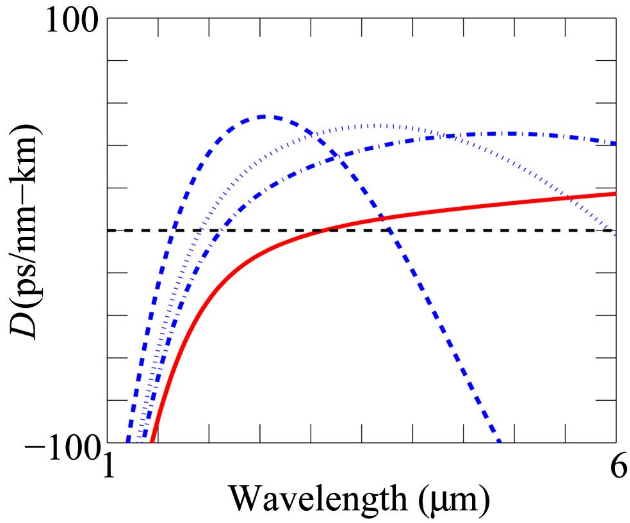

Fig. 1. (Color online) Blue dashed, dotted, and dashed-dotted curves represent the dispersion as a function of wavelength for a pitch of 2 μm, 3 μm, and 4 μm, respectively. The red solid curve shows the material dispersion. The black dashed line indicates zero dispersion.

and the Raman response function are different. For the nonlinear refractive index n_2, we used $n_2 = 4.2 \times 10^{-18}$ m/W at a wavelength of 2 μm, which we obtained from Table 1 of [15] and Fig. 5 of [16]. The Raman gain for As_2S_3 chalcogenide fibers used in our simulation was measured at the Naval Research Laboratory [17]. In Fig. 2, we show the material loss for an As_2S_3 chalcogenide fiber, measured at the Naval Research Laboratory, which has a low loss region between 2 μm and 6 μm. The material loss peak around the wavelength of 4 μm is due to H-S impurities.

We used this two-stage procedure to find an optimized pitch of the As_2S_3 chalcogenide PCF that maximizes the generated power in the wavelength range between 3 μm and 5 μm. We set the length of the fiber to be 0.5 m. Figure 3 shows the ratio of the power generated between 3 μm and 5 μm to the total input power as a function of pitch. The input signal is a hyperbolic-secant pulse with a peak power of 1 kW and an FWHM of 500 fs. More than

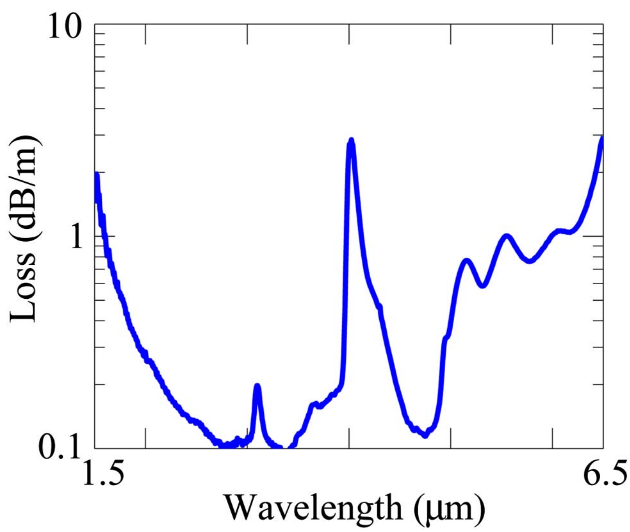

Fig. 2. (Color online) Material loss for As_2S_3 chalcogenide fiber.

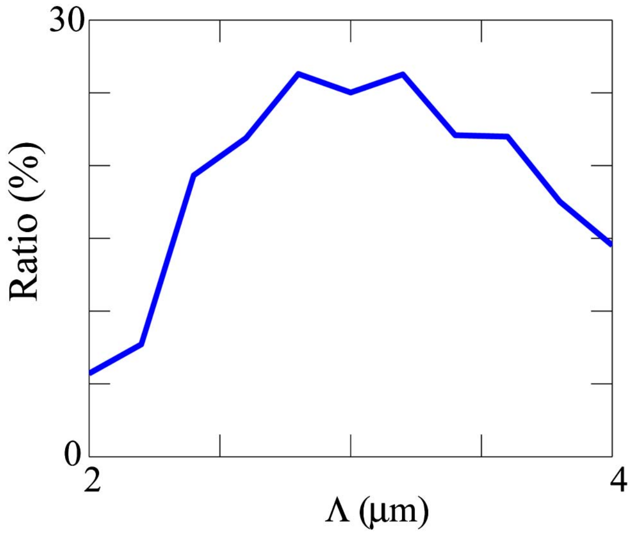

Fig. 3. (Color online) Ratio of power generated between 3 μm and 5 μm to the total input power as a function of pitch.

25% of the input power is shifted into the region between 3 μm and 5 μm when the pitch is between 2.8 μm and 3.2 μm. The main mechanisms for supercontinuum generation are soliton fission and the soliton self-frequency shift. For a pitch of 2 μm, the dispersion quickly decreases beyond a wavelength of 2.5 μm, as shown in Fig. 1. The wavelength shift due to the soliton self-frequency shift has been shown to be proportional to the dispersion [18]. Hence, a PCF with a small pitch cannot generate much power at wavelengths that are higher than 2.5 μm, and the power generated between 3 μm and 5 μm is small, as shown in Fig. 3. A fiber with a larger pitch will have a larger effective mode area and a smaller nonlinearity, leading to a small amount of supercontinuum generation. Hence, a fiber with a larger pitch will generate a small amount of power between 3 μm and 5 μm, as is shown in Fig. 3. Figure 4 shows the spectrum of the supercontinuum generation using a PCF with $\Lambda = 3$ μm.

Figure 5 shows the total generated power in the region between 3 μm and 5 μm and the ratio of the total generated power to the total input power as a function

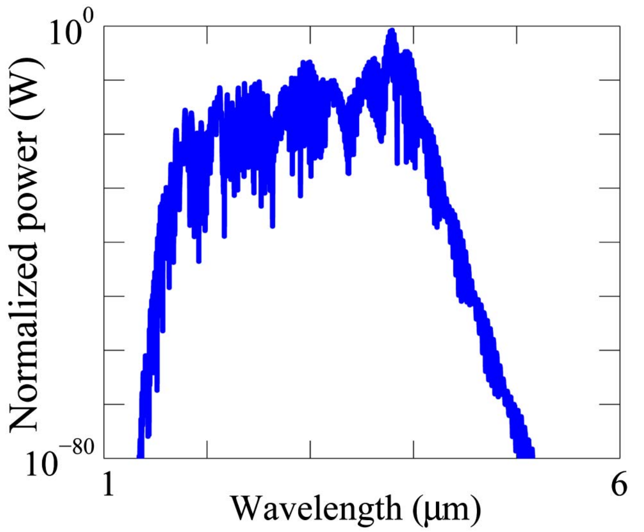

Fig. 4. (Color online) Spectrum of the supercontinuum generation using an As_2S_3 chalcogenide PCF with $\Lambda = 3$ μm.

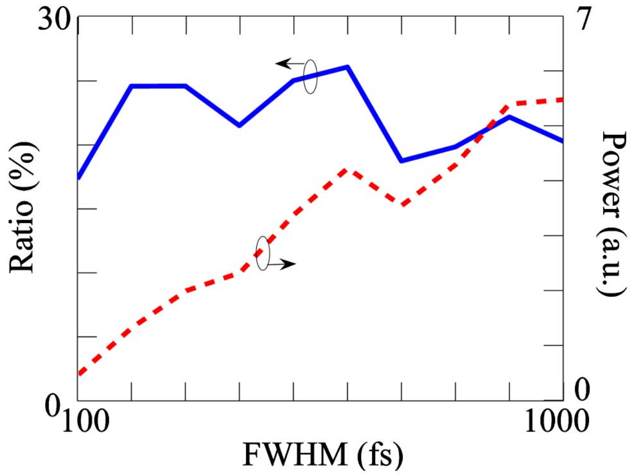

Fig. 5. (Color online) Total generated power in the region between 3 μm and 5 μm and the ratio of the total generated power to the total input power as a function of the FWHM of the input pulse. The input peak power is fixed at 1 kW. The pitch of the As_2S_3 chalcogenide PCF is set to 3 μm.

of the FWHM of the input pulse. When the pulse width increases, the total generated power increases almost linearly. The ratio of the total power generated between 3 μm and 5 μm to the total input power is between 15% and 25% for all pulse widths that we investigated, as shown in Fig. 5. Figure 6 shows the total generated power in the region between 3 μm and 5 μm and the ratio of the total generated power to the total input power as a function of input peak power. The total generated power increases almost linearly when the peak power is between 0.2 and 1.5 kW. However, the ratio of the total generated power to the total input power increases until the peak power reaches 0.8 kW. The roughly linear increase in the total generated power as the FWHM or peak power of the input pulse increases yields a relatively constant

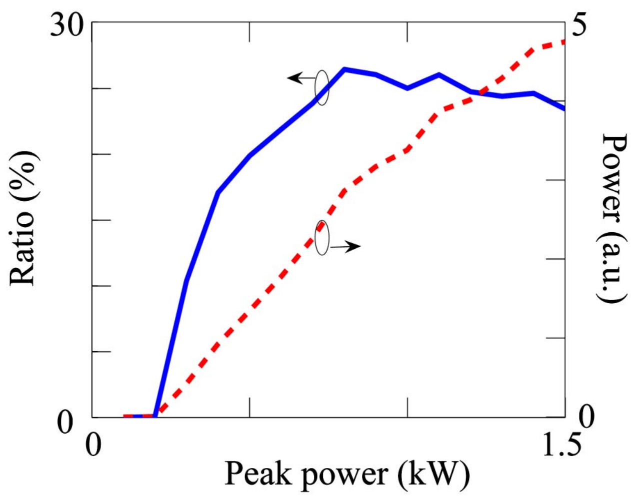

Fig. 6. (Color online) Total generated power in the region between 3 μm and 5 μm and the ratio of the total generated power to the total input power as a function of the input peak power. The FWHM of the input pulse is fixed at 500 fs. The pitch of the As_2S_3 chalcogenide PCF is set to 3 μm.

ratio of the total generated power to the total input power, as we show in Figs. 5 and 6.

In conclusion, we have shown that it is possible to use supercontinuum generation in an As_2S_3 chalcogenide PCF with an input wavelength of 2 μm, an input FWHM of 500 fs, and a peak power of 1 kW to shift more than 25% of input power into a region between 3 μm and 5 μm. We optimized the waveguide and pulse parameters, and we found $\Lambda = 3$ μm, an input FWHM of 500 fs, and a peak power of 1 kW. The broad dispersion profile and high nonlinearity in As_2S_3 chalcogenide glass are essential for this application.

The authors thank R. J. Weiblen for useful comments.

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