12th Optoelectronics and Communications Conference/16th International Conference on Integrated Optics and Optical Fiber Communication (OECC/IOOC2007)
Technical Digest, July 2007, Pacifico Yokohama

13C1-5

Spatial Evolution of Supercontinuum Generation along a Varying Dispersion Tapered Fiber

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Abstract: Ultrabroad supercontinuum spectrum generation in the anomalous- and normal-dispersion regimes of a narrow-waist tapered fiber is theoretically analyzed by taking into account of the dispersion coefficient and effective core area varying along taper transition region.

1. Introduction

Ultrabroad and high coherence supercontinuum (SC) spectra have been obtained using femtosecond laser pulses in tapered fibers [1], which have some unique advantages of strong zero-dispersion wavelength (ZDW) shift, plain physical structure, short length and home-made producing method [2-3]. In this paper, we theoretically discuss the femtosecond pulse propagation through the tapered fiber including the narrow-waist region and the transition regions with decreasing or increasing diameters. The spectral intensity and the unwrapped spectral phase are shown how they evolve along the propagation distance.

2. Theoretical Model

Figure 1 shows the analytical profile of a biconical tapered fiber with 4 mm long untapered regions, 15mm long transition regions, and 75 mm long waist with a uniform diameter of 2.3 μm. This is similar to the one described by Teipel et al. [2], in which SC spectrum over 500-1100 nm was generated. All simulations presented here are made with the Corning SMF-28 fiber parameters. The transitional region is assumed to obey an exponentially decaying and expanding shape as an adiabatic process for single-mode propagation.

The propagation constant of the fundamental mode at each propagation distance is obtained by solving the vector wave equation using the finite element method with analytical boundary conditions [4]. Then we know that the group velocity dispersion (GVD) varies from normal-dispersion to anomalous-dispersion regime along the preceding transition fiber. The effective core area A_{eff} of the fundamental mode is also calculated by scalar field distributions for the guided mode. Figure 2 shows the A_{eff} as a function of fiber diameter at a wavelength of 800 nm. The variation of the A_{eff} is nonlinear because the power leaks from the core into cladding and then into the surrounding air when the fiber diameter decreases. The

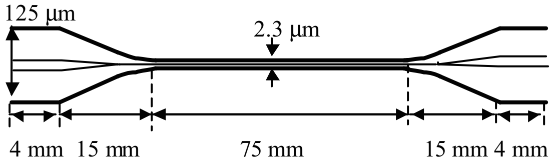

Fig.1. Structure of a tapered fiber.

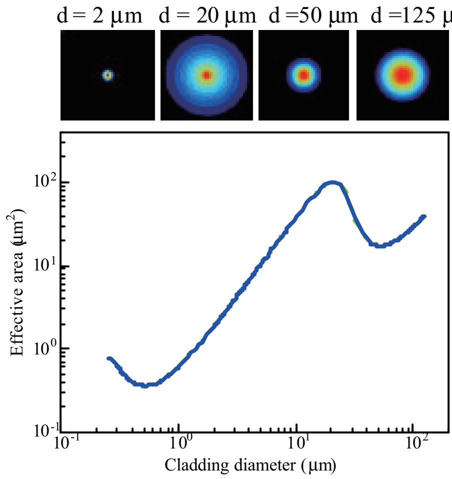

Fig.2. Effective area and intensity distribution for different taper diameters at λ = 800 nm.

intensity distribution for the diameters of 2, 20, 50, and 125 μm was shown in the upper graphs of Fig. 2. For the fiber under test, A_{eff} is 2.4 μm^2 at the waist region. Thus, the important nonlinear parameter γ, which is defined as $\gamma = n_2\omega_0/cA_{eff}$, increases to 98.2 W^{-1}km^{-1} for a nonlinear refractive index n_2 = 3.0 × 10^{-20} m^2/W. This value is approximately 17 times larger than the one at the untapered region and the resulting spectral broadening is induced intensively in the nonlinear processes.

To describe the evolution of intense femtosecond pulses through the tapered fiber, we use the extended NLSE [5] which models enhanced nonlinear effects including SPM, self-steepening and stimulated Raman scattering (SRS). The generalized Raman scattering susceptibility is approximated as a harmonic oscillator model [6] for the molecular vibrations to the Lorentzian function.

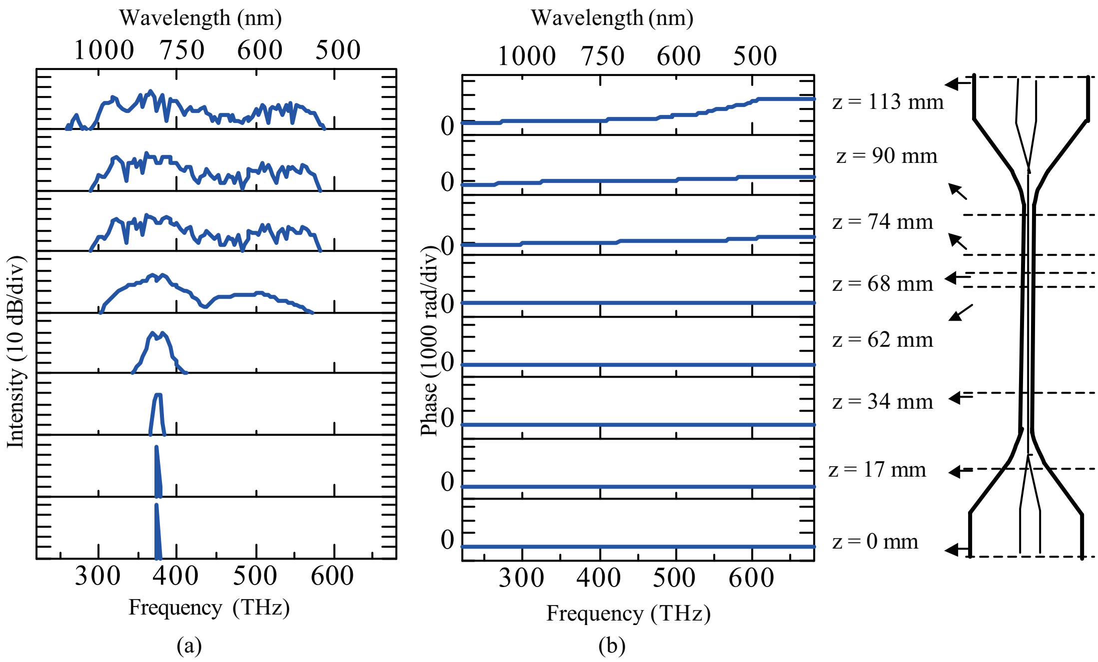

Fig. 3. Evolutions of spectral (a) intensity and (b) phase along the tapered fiber for the power of 100 mW.

3. Numerical Results

The NLSE is numerically solved by means of a split-step Fourier method [5] and the enlargement of the SC spectral width due to the combined effects of dispersions and nonlinearities can be evaluated quantitatively. We have assumed the input ultrashort pulse to be hyperbolic secant type with a center wavelength of 800 nm and repetition rate of 80 MHz. These parameters are typical of those used in the abovementioned experimental works [2].

Figure 3 shows the evolutions of (a) spectral intensity ($=(\mathrm{Im}[A(z,f)])^2+(\mathrm{Re}[A(z,f)])^2$) and (b) spectral phase ($=\tan^{-1}(\mathrm{Im}[A(z,f)]/\mathrm{Re}[A(z,f)])$) at different distances for output average power of 100 mW and input pulse duration of 380 fs. Here, the phase is processed by unwrapping method in order to maintain a smooth phase shift exceeding over 2π rad. The upper and lower abscissas of these figures denote a corresponding wavelength and frequency, respectively. It is evident in Fig. 3(a) that the spectra broaden slightly but almost symmetrically at the initial propagation stage. However, when the pulse propagates down the distance of 68 mm, the spectrum extends its widths dramatically and then remains almost unchanged. The output spectrum covers approximately one octave at the 20-dB level and exhibits a better agreement with the experimental than the simulation result reported in the same Ref. [2].

On the other hand, Fig. 3(b) shows that the corresponding phase evolves in a different way, i.e., it increases significantly after the point of 68 mm, which is called the "critical distance" in our recent paper [6]. This behavior can be understood by noting that the spectral components, which cover not only the anomalous regime but also the normal regime, are accumulated continuously as the SC spectrum propagates down the fiber [5].

It is worthy to note that the critical distance is varied with different dispersion of fiber and/or pulse conditions in addition to average power. In this regard, a highly sophisticated design of the tapered fiber should be taken into account in terms of the critical distance.

4. Conclusions

In summary, we have conducted numerical studies of ultrashort pulse propagation in varying dispersion tapered fibers with the anomalous- and normal-dispersion and effective core area varying along the taper. It is found that there are drastic phase variations in the output taper transition region. We have also pointed out that the critical distance in the tapered fiber is a useful parameter for estimating the SC spectrum and phase evolutions.

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