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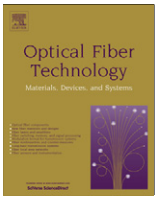

Invited Papers

From zero dispersion to group index matching: How tapering fibers offers the best of both worlds for visible supercontinuum generation

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ABSTRACT

We provide an experimental study of the nonlinear optical effects which can be enhanced in order to produce visible supercontinua in photonic crystal fibers. We examine individual uniform fibers and discuss the physical origins of the resulting supercontinua. We then examine tapered supercontinuum fibers which exploit the advantages of our individual uniform fibers at different points along the length of the taper. We demonstrate reproducible control of taper shape.

1. Introduction

Nonlinear processes in an optical fiber occur when an optical field with defined initial characteristics propagates through a length of fiber [1]. The parameters of the input field and the properties of the fiber itself determine the nonlinear processes which take place and the form of the optical field at the output. Generally, the input may have a complicated form in time, and possibly a nontrivial polarization state too. Under the correct conditions, the nonlinear propagation may result in supercontinuum generation, which usually results from the interplay between several different nonlinear processes [2]. The relevant properties of the fiber include not only the different time-dependent components of the nonlinear response (which are usually determined by the material of which the fiber is formed) but also its linear properties. These linear properties determine the extent to which the different known nonlinear effects take place, and how they manifest. The most important effects include self-phase modulation, soliton formation, soliton propagation and break-up, Raman self-scattering, dispersive wave generation, group-index matching, four-wave-mixing and optical wave breaking. Control of the linear properties of the fiber over length scales which may vary from millimeters to kilometers is the key to controlling supercontinuum generation, and correct design of the fiber is thus critical. Despite over a decade of intensive research into supercontinuum generation in photonic crystal fibers, and many significant insights into the underlying physics, the complexity of the supercontinuum generation process means that progress remains to be made. The inverse nature of the problem – "What fiber design will best produce the desired output?" – coupled with the range of different pump wavelengths and pulse lengths being used means that designing fibers for supercontinuum generation remains a fertile research area. This paper describes just a couple of the advances made over the last few years in understanding how to do this. Only a very brief description of the physical background is presented as there is at least one book and several excellent review papers on this subject [2–5], and the basic physics is well known. The bulk of the paper relies on using experimental case studies of some specific fibers to illustrate some of the mechanisms relating fiber design to supercontinuum spectrum.

2. Background physics

2.1. Nonlinear effects

The basic processes involved in nonlinear propagation in optical fibers are generally well understood. Critical parameters of the optical fiber which determine the nonlinear evolution are the nonlinear coefficient, which incorporates both the value of n_2 in the material of which the fiber is formed and the effective area of the guided mode (often assumed to be independent of wavelength), and the Raman response, again a property of the material. The dispersion of the guided mode, including the group index and the group velocity dispersion, are of special importance. If there is any significant polarization dependence in the fiber, then that will influence the observed effects. Out of these parameters, the spectral dependence of the dispersion is surely the most important, and is the mechanism through which the fiber design most critically affects the supercontinuum.

2.2. Anomalous dispersion and soliton formation

The dispersion of the guided mode of a fiber most generally refers to the variation of the propagation constant with wavelength.

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Practically, it is useful to explicitly consider not only the propagation constant or the associated effective mode index, but also the group velocity (and group index) and the group velocity dispersion (GVD), which depend on the first and second derivatives of the propagation constant respectively. *Normal* values of the group velocity dispersion correspond to short-wavelength components within a pulse travelling more slowly than long-wavelength components. Because self-phase-modulation in silica fibers generates red-shifted radiation at the leading edge of pulses and blue-shifted radiation at their trailing edge, normal dispersion and self-phase modulation between them cause very rapid dispersion of a pulse propagating in the non-linear regime. On the other hand, if the group-velocity dispersion is *anomalous* then it is the shorter-wavelength ("blue") components of the pulse which travel more quickly. When combined with self-phase modulation, this makes it possible to create solitons in the fiber, which propagate over unexpectedly long distances without dispersing due to the interplay between the linear and nonlinear effects. While the solitons propagate they gradually change their wavelength due to intra-pulse Raman scattering, an effect known as the soliton self-frequency shift. As a result of this they shift to longer wavelengths as they propagate, shifting further for longer fiber lengths and faster for shorter pulses. If the group-velocity dispersion which the soliton experiences as it propagates changes, either because of the change in its wavelength or because the fiber changes along its length, then the length of the soliton will change as well, becoming shorter if the dispersion decreases or longer if the dispersion goes up. Ultimately, the soliton will continue to shift until it no longer has enough energy, or until it becomes too long (if the GVD is increasing), or until it approaches a zero-dispersion wavelength beyond which the GVD becomes normal.

2.3. Group index matching

When the solitons propagate as nonlinear pulses they have the potential to affect the propagation of light at other wavelengths, through the instantaneous nonlinear response of the glass (four-wave mixing, cross-phase modulation), provided that the two wavelengths co-exist simultaneously in the material [6–8]. The variation of group index with wavelength is key to determine whether this is the case – pulses with different central wavelengths with the same group index will propagate at the same speed and thus have the potential for nonlinear interaction over extended lengths. The group index versus wavelength curve is frequently cup-shaped, with the minimum point, where the slope is zero, corresponding to the zero-GVD wavelength (the bottom of the cup) and with the values increasing as one moves to shorter and longer wavelengths. This shape of curve offers opportunities for group-index matching between the extremes of the spectrum, as the shortest and longest wavelengths can potentially propagate at the same group velocity on the different arms of the group-index curve. The GVD is anomalous at wavelengths longer than the zero point (group index rising with wavelength) and normal on the shorter-wavelength side (group index falling with wavelength). Solitons can therefore be formed at wavelengths longer than the zero-dispersion wavelength and will shift to yet longer wavelengths, climbing up the group-index curve and slowing down as they do so. It is well documented that these solitons can create a potential well which can trap short-wavelength radiation, dragging the short-wavelength light up the group-index curve – and shifting it to yet shorter wavelengths – as they themselves shift to longer wavelengths [8]. The shortest wavelengths generated in the supercontinuum are then determined by the extent of the soliton shift to longer wavelengths, and by which short wavelengths which are group-index matched to the long wavelengths at that point. This is determined by the shape of the group index curve for the specific fiber being used.

3. Fiber design

3.1. Properties of uniform fibers

The importance of the fiber dispersion in determining the generated supercontinuum spectrum makes the control of the dispersion profile a key factor in fiber design. Photonic crystal fibers offer opportunities for varying the dispersion over a wide range. For the study reported here we have chosen to focus on fibers with a high air fraction in their cladding, notwithstanding the varied and useful properties which are attainable with different designs [9–14]. For high-air-fraction claddings it is known that the basic dispersive properties of the fundamental mode are well approximated by the properties of a circular strand of silica surrounded by air [15], and this approximation has been used to produce the plots shown in Fig. 1 [16]. Fig. 1 shows the calculated group index (top) and group velocity dispersion (bottom) of a strand of silica surrounded by air, for three different values of the diameter (d), 6 μm, 4 μm and 2 μm. The pump wavelength used in our experiments in this work was 1060 nm and these fiber sizes have been chosen to have features relative to that wavelength, but are anyway representative of the general trends for such fibers.

3.2. Tapered fibers

Tapered supercontinuum fibers formed during the fiber drawing process have been used to demonstrate supercontinua which cannot be achieved in uniform fibers from a given pump source. In particular, attention has focused on extending the short wavelength edge of continua pumped by 1060 nm sources to below 400 nm [17,18]. These efforts are largely driven by potential applications for supercontinua containing ultraviolet light in fluorescence imaging and the commercial availability of cheap, robust 1060 nm pump sources [19,20]. The basic physics of supercontinuum generation discussed above for uniform fibers does not change in the case of tapers, but a taper can be fabricated such that the different nonlinear effects are enhanced and exploited at different points along its length. This allows for a simple supercontinuum source consisting of a pump laser and tapered photonic crystal fiber to be tailored for a potential application. Below we deconstruct simple linear tapers to show how the different effects which lead to a full supercontinuum can be exploited at key stages along the taper length.

4. Fiber fabrication and experiments

Three fibers approximating to the strands described above were fabricated from the same preform, which was formed using the stack and draw process. Scanning electron micrographs of the fibers are shown in Fig. 2 (top). The three fibers were drawn by altering the drawing speed during the draw, with other parameters remaining constant. In addition to lengths of uniform fiber of these three core sizes, several nominally identical tapered fibers were also drawn, one after another, by increasing the fiber draw speed and subsequently decreasing it again under computer control such that the resulting tapers all had a linear reduction in outer diameter of a factor of three over a 5 m length. Data recorded during the taper draw is also shown in Fig. 2 (middle and bottom). By varying the speed of the capstan in different ways, taper profiles other than the linear profile shown in Fig. 2, bottom could easily have been produced. The resulting tapers had an input core size of 6 μm and tapered to a 2 μm core at the small end over a length of around 5 m as shown, giving the input end similar group index and group velocity dispersion to the 6 μm strand shown above, and the output end similar characteristics to the 2 μm strand (as shown in Fig. 1). The taper