Generation of supercontinuum light in photonic crystal fibers

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ABSTRACT. I summarize the recent studies on the supercontinuum generation (SC) in photonic crystal fibers (PCF) with emphasis on the studies of nonlinear optical effects responsible for the supercontinuum generation, including self-phase modulation (SPM), four-wave mixing (FWM) and stimulated Raman scattering (SRC).

1 Introduction

When interacting with intense laser pulses, as a consequence of interconnected nonlinear responses, materials such as crystal or glass can generate new frequencies which broaden the spectrum spanning over the whole visible region to infrared. Because of this unusual and rather impressive property, together with its coherence property, the generated light is called a supercontinuum (SC) or “white light”. The first observation of SC was made by Alfano and Shapiro in 1970 in bulk crystals such as calcite using single picosecond pulses[1]. In 1999, Ranka et. al. demonstrated the generation of SC in a photonic crystal fiber (PCF) with extremely small solid-core using a continuous train of femtosecond pulses (Fig. 2). The generated SC spans over 550 THz in spectral width, extending from the violet to the infrared[2]. Since then, there has been numerous researches on SC generation based on PFC and many techniques have been developed using different types of PFC, including micro-structured fibers, tapered fibers and highly nonlinear dispersion shifted fibers (HNLF), and employing different pumps, femtosecond, picosecond and even nanosecond pulses. Each type of PCFs exhibits different behaviors, but essential nonlinear effects contributing to the SC generation are common to all. This report presents those nonlinear optical effects responsible for the generation of SC, including self-phase modulation (SPM), four-wave mixing (FWM) and stimulated Raman scattering.

It should be also mentioned here that the advent of the SC generation based on PCFs have made significant impacts in many areas of science and technology. Because of the special physical structure and strong nonlinearities, PCF can generate SC with relatively low energy input, making SC generation more accessible to many researchers in different fields. It has found important applications in spectroscopy, imaging, fiber communication, metrology and more. Among a myriad of fields that can be benefited from SC, it has brought a significant breakthrough especially to the field of frequency metrology, which can be remarked by a share of the 2005 Noble prize awarded to J. Hall and T. Häsusch for their pioneering work on the carrier-frequency control and stabilization of ultrashort pulses. SC has more potential to bring another breakthrough to scientific and technological communities, which signifies the importance of the subject of this report.

2 Nonlinear effects in PCF

The advantage of PCFs in the SC generation are that PCFs confine the beam in a very small diameter and nonlinear interaction occurs over a long distance; therefore, highly nonlinear effects can be achieved with relatively low pulse energy. Mechanisms of SC generation involve a rather complicated interplay between different nonlinear effects. In last decade, there has been numerous researches, both theoretically and experimentally, to understand the physical origins of the SC generation. As commonly understood,
the generation and propagation of SC waves are described by the nonlinear Schrödinger equation. It has been discovered that the temporal width of the pump pulse is a critical factor in determining the dominant effects in the SC generation in PCF. In femtosecond regime (<100 fs), the dominant mechanism for the SC generation is the self-phase modulation (SPM) induced by strong field interaction\cite{6}. For longer pulses, in picosecond and even nanosecond regime, the four-wave mixing (FWM) and stimulated Raman scattering (SRS) become the dominant mechanisms while SPM make negligible contribution to the SC generation\cite{7}. In the sections, I present those nonlinear effects characterized by the temporal width of the pump pulses.

2.1 Femtosecond pump

2.1.1 Self-phase modulation (SPM)

When a very intense, ultrashort fs laser pulse is propagating through a $\chi^{(3)}$, the optical Kerr effect (OKE) produces the intensity-induced index of refraction:

$$n(t) = n_0 + n_2 I(t)$$

where $I(t)$ is the instantaneous intensity. Consequently, the phase of the carrier wave is modulated as

$$\phi = \phi_0 + \phi_{NL} = \phi_0 + \frac{2\pi}{\lambda_0} n_{NL} L = \phi_0 + \frac{2\pi}{\lambda_0} n_2 I(t) L$$

$$\phi_{NL}(t) = \frac{2\pi}{\lambda_0} n_2 I(t) L$$

where L is the length of the crystal. By realizing that the instantaneous frequency is the first time derivative of the phase, one finds

$$\omega(t) = \omega_0 + \delta \omega(t)$$

where

$$\delta \omega(t) = -\frac{d\phi_{NL}}{dt} = -\frac{2\pi n_2 L}{\lambda_0} \frac{dI}{dt}$$

(1)
Figure 3. GVD coefficient of PCF and silica. Notice that PCF has near zero-dispersion around 647 nm. (Adapted from Coen et al. [4])

Figure 4. Experimental result shows the evidence of soliton formation, marked by an arrow. Pumped at 810 nm. (Adapted from Tartara et al. [5])

is the spectral broadening caused by the SPM[4]. Eq. (1) indicates that the spectral broadening depends on the length of the crystal and the steepness of the temporal profile of the propagating pulse. If a PFC is designed to have near-zero dispersion at the pump frequency (see Fig. 3), the pulse propagates through the fiber without experiencing significant walk-off between different frequency components, forming one optical soliton.

When the beam is confined in a small diameter and guided through over a long distance in a nonlinear crystal, highly nonlinear effects can occur. Instead of forming a train of identical broadened pulses at the original repetition rate (which makes the comb structure), parts of modes in the frequency spectrum combine to make one soliton, propagating at the group velocity for that frequency. The original pulse spectrum splits into independent solitons of different frequencies hence different group velocities, and the regular structure of the frequency comb is lost (Fig. 4). In this figure, each peak corresponds to formation of solitons, with an arrow on a particular soliton centered around 1100 nm. It shows that the broadened spectral features such as seen in Fig. 2 cannot be explained by the action of SPM alone. Evidence of the presence of the other nonlinear effects become more obvious when longer pulse is used, which is presented in the next section.

A remarkable feature of SPM generated SC is that the mode structure (frequency comb) of the pump pulse is not altered during the SC generation[9]. This plays a critical role in the frequency metrology and carrier-phase stabilization applications where the mode structure of the pulse is an essential parameter.

2.2 Pico-(nano-)second pump

2.2.1 Four-wave mixing (FWM)

When the pump pulse is a few hundred femtosecond or longer, the SPM becomes less effective because $\frac{dI}{dt}$ is not large enough. In this regime, the FWM becomes the dominant mechanism for the SC generation. The FWM phase-matching and energy conservation among interacting waves are

$$2k_{\text{pump}} = k_{\text{signal}} + k_{\text{idler}} + 2\gamma P$$ (2)
where $k$ are the wavevectors, and $\omega$ the frequencies; $P$ is the pump power; and $\gamma$ is the nonlinear coefficient of the fiber,

$$\gamma = \frac{2\pi n_2}{\lambda_0 A_{eff}}$$

where $A_{eff}$ is the effective area of the fiber and $\lambda_0$ is the pump wavelength\[7\]. Strength of the FWM is determined by the nonlinear index of refraction, $n_2$, and the phase-matching condition (Eq. (2)). As in the case of femtosecond pulses, FWM is most effective when the pump pulse is at the anomalous (near-zero) dispersion of the material. In this region, the generated spectrum are temporally overlapped, thus enhance the effect furthermore. Indeed, this supports the observed fact that the FWM is more effective when pumped with longer pulses whose temporal overlap is large. It should be noted, however, that modes structure of the pulse (frequency comb) are modified in the SC when generated via FWM.

2.2.2 Stimulated Raman scattering (SRS)

Another mechanism that comes into play for the case of longer pump pulse is the stimulated Raman scattering. The SRS becomes especially remarkable when the phase-matching condition in Eq. (2) is not fully satisfied and the FWM becomes less effective.

The SRS is described by the following amplitude coupled equations;

$$\frac{dA_s}{dz} = -\alpha_s A_s + \kappa_s A_a^* e^{i\Delta kz} \quad (3)$$

$$\frac{dA_a}{dz} = -\alpha_a A_a + \kappa_a A_s^* e^{i\Delta kz} \quad (4)$$

where $A_s$ and $A_a$ are the field amplitude of the Stokes and anti-Stokes waves, respectively and $\Delta k$ is defined as

$$\Delta k = 2k_L - k_s - k_a$$

\[5\]
where $k_i$ are the wavevectors for laser (pump), the Stokes and anti-Stokes[10]. It is evident that the sum of $k_s$ and $k_a$ are always larger than $2k_L$ in a material with normal (or near-zero) dispersion. Therefore, from Eq. (5), perfect phase matching ($\Delta k = 0$) can always achieved if the Stokes propagates at some non-zero angle with respect to the laser wave[10]. This is the reason why SRS is insensitive to the phase-matching. If angles are not the phase-matching angles, $\Delta k$ is large, and the exponential term in Eq.(3) and Eq.(4) becomes negligible due to cancellation from rapid oscillating phase in distance. For these directions, the two equations decouple, and the Stokes sideband experiences gain while the anti-Stokes sideband experiences loss. On the contrary, if the direction is such that $\Delta k$ is small, the two equations are coupled, creating more complex interplay between the Stokes wave and the anti-Stokes wave as well as parametric FWM[4]. Those phenomena are well observed in the SC generation in PCF with picosecond pump pulses, shown in Fig. 5. In this figure, the anti-Stokes has a large peak compared with the Stokes, indicating other effects such as the FWM also plays a role.

3 Conclusion

As presented above, SC is generated as a result of a range of interconnected nonlinear effects. Contribution to the SC generation from each effect has been studied experimentally in both femtosecond regime and pico-(nano)second regime, and mostly agree with theoretical prediction. Yet, the exact treatment of the SC generation is extremely complex, due to complicated interplay of various nonlinear effects, especially when femtosecond pulses are used. As demonstrated by Ranka et. al., this complex interplay of a various nonlinear effects give rise to the impressive octave-spaning SC (Fig. 2).

4 References


8. J. W. Nicholson, M. F. Yan, P. Wisk, J. Fleming, F. DiMarcello, E. Monberg, A. Yablon, "All-fiber,
