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ARTICLE

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NUMERICAL SIMULATION OF SUPER CONTINUUM GENERATION IN TAPERED OPTICAL FIBERS

KAMAL HUSSAIN*

Fibers with high nonlinearity are suitable for broadband super continuum generation. Photonic crystal fiber, highly nonlinear fiber and tapered optical fiber are thus well suited for super continuum generation as they exhibit anomalous dispersion and nonlinearity. For numerical simulation we need to consider higher order dispersion and nonlinear terms in the equation for pulse evolution in a single mode fiber. These values have been obtained from recent publications. Using this simulation we show the broadband super continuum generation in tapered optical fiber.

Introduction

Optical pulses propagating through fibers are affected by the dispersion and various other nonlinear effects present in the fiber. The various nonlinear effects present within the fiber are self-phase modulation, cross-phase modulation, four-wave mixing, stimulated Raman scattering, and more. The main effect of these nonlinear phenomena is to generate new frequencies, hence broadening of the spectrum. Such broadening can exceed 100 THz and extends from violet to infrared. This type of spectrum broadening is termed as super continuum (SC) generation. The phenomenon was first observed in solid and gaseous media with nonlinearities around 1970 [1]. During the last few decades SC has found various applications ranging from nonlinear frequency conversion, optical coherence tomography, optical frequency comb, micromachining, light detection and ranging (LIDAR) and more[2].

For the generation of SC a power greater than the threshold power is required. It can be of the order of 1000 W and more. To have such high power stable femto second pulses are required. Although SC has been obtained with picoseconds pulses, but with femto second pulses, the SC spectrum is quite broad. Fig.1. shows a schematic for the generation of SC generation in a tapered fiber. Such pulses can be obtained from Ti: Sapphire lasers. The nonlinearity of single-mode silica optical fibers is high due to their low loss and small effective area[3]. The nonlinearity can be increased many folds by heating a small length of the fiber and pulling it to have a tapered portion. The cross-sectional width of tapered portion of the fiber may be reduced to more than 10 times the width of the original width. This enhances the nonlinearity of the fiber and thus the pulse propagating through the tapered region of the fiber easily overcomes the threshold value required for SC generation[4].

Theory and Numerical Simulation:

Since pulse propagation in an optical fiber is an electromagnetic phenomenon, it is also governed by the Maxwell's equations. The equation for the field of the propagating optical pulse in a single-mode fiber is given by[3],

$$\vec{E}\left(\vec{r},t\right)=\frac{1}{2}\hat{x}\left[\varepsilon\left(\vec{r},t\right)e^{-t\omega_0 t}+c.c.\right] \tag{1}$$

* Department of Physics, Belda College, Belda, Paschim Medinipur, W.B.-721424, e-mail: kamalhussain123@gmail.com

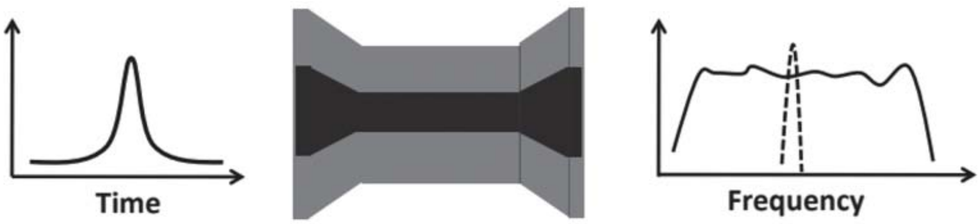

Fig. 1. Schematic of a tapered optical fiber. The dotted curve represents the input spectrum.

where, $\varepsilon(\vec{r},t) = F(x,y)\,A(z,t)e^{i\beta z}$ with $F(x, y)$ as the transverse profile and $A(z, t)$ as the field envelope. The c.c. is an abbreviation for complex conjugate part of the field. The propagation constant is given by $\beta(\omega)$. The propagation constant when expanded around the operating frequency ω_0, we obtain

$$\beta(\omega) = n(\omega)\frac{\omega}{c} = \beta_0 + \beta_1(\omega-\omega_0) + \frac{1}{2}\beta_2(\omega-\omega_0)^2 + \frac{1}{6}\beta_3(\omega-\omega_0)^3 + \ldots \quad (2)$$

where $\beta_1 = \frac{d\beta}{d\omega} = \frac{1}{v_g}$, V_g being the group velocity and β_2 is the group velocity dispersion. λ represents the operating wavelength which is 1050 nm in this case. Neglecting loss for the small length of the tapered fiber and considering higher order dispersion effects and nonlinear phenomena the pulse propagation equation in fiber can be written as[3]

$$i\frac{\partial A(z,T)}{\partial T} = -\sum_{k\geq 2}\frac{i^k\beta_k}{k!}\frac{\partial^k A(z,T)}{\partial T^k} - \gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial T}\right) \times \left[A(z,T)\int_{-\infty}^{+\infty} R(T')\left|A(z,T-T')\right|^2 dT'\right] \quad (3)$$

where $T = t - z/v_g = t - \beta_1 z$ is the co-propagating frame timewhere the frame of reference is considered to propagate along the length of the fiber with velocity same as the group velocity of the pulse and $\gamma = \frac{n_2\omega_0}{cA_{eff}}$ represents the nonlinearity with A_{eff} as the effective cross-sectional area. The stimulated Raman scattering is given by $R(T) = (1-f_R)\delta(T) + f_R h_R(T)$ with f_R = 0.18 and $h_R(T)$ is the Raman resonance function. The simulation may be done by following either the split-step Fourier method [3] or the direct integration method[5]. The values of the higher order dispersion parameters (β_k's) are evaluated from the $\beta(\omega)$ of the material. The nonlinearity parameter γ = 150 W^{-1}/km and the values of the β_k's used in the simulation are given in Table 1. For the simulation a *sech* pulse of 25 fs pulse width with a peak power of 2 kW is considered. The length of the tapered fiber considered in the simulation is 20 cm.

Simulation Results

Figure 2 (a) shows the evolution of the output spectrum and Figure 2(b) show the evolution of the output pulse with propagation along the length of the tapered fiber.

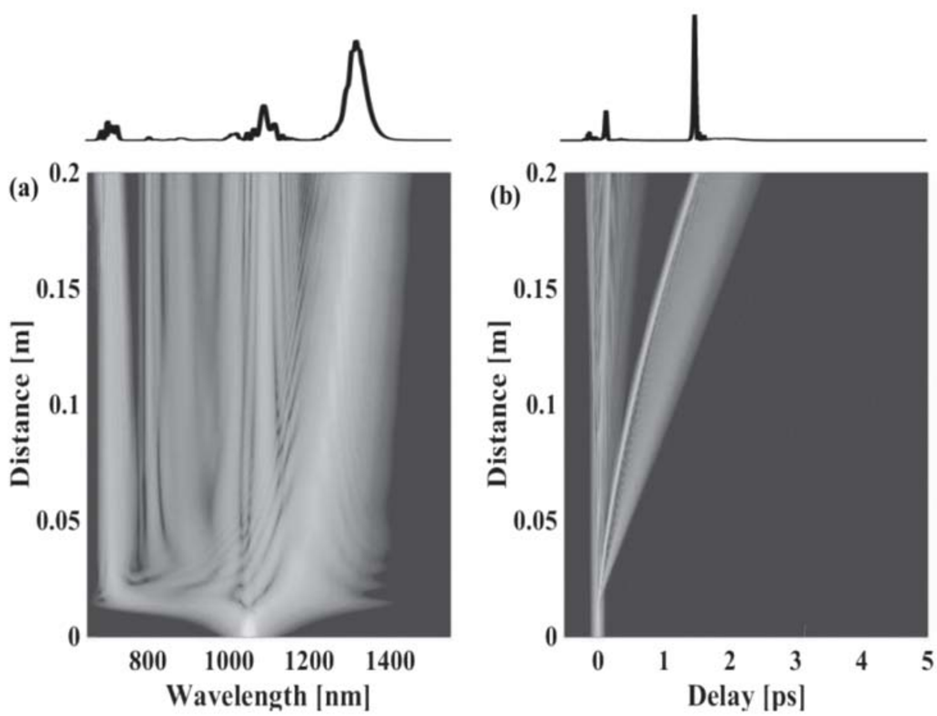

Fig. 2. (a) Shows the evolution of SC spectrum along the length of the fiber (b) Shows the pulse delay as it propagates along the length of the fiber.

Table 1. Parameters of the Fiber used in the Simulation[6].

Parameter	Symbol	Value with units
2nd order disp. parameter	β_2	-1.276×10^{-2} $ps^2.m^{-1}$
3rd order disp. parameter	β_3	8.119×10^{-5} $ps^3.m^{-1}$
4td order disp. parameter	β_4	-1.321×10^{-7} $ps^4.m^{-1}$
5th order disp. parameter	β_5	3.032×10^{-10} $ps^5.m^{-1}$
6th order disp. parameter	β_6	-4.196×10^{-13} $ps^6.m^{-1}$
7th order disp. parameter	β_7	2.570×10^{-16} $ps^7.m^{-1}$

It clearly shows that after travelling a short distance through the taper fiber, the broadening of the spectrum takes place. Figure 2(b) shows that due to the interplay of the dispersion and nonlinear terms, the output pulse is gets delayed in time. The curves above Figure 2(a) and 2(b) shows respectively the output spectrum and output pulse obtained at the end of the tapered fiber.

Conclusion

This work shows the potential of the numerical simulation to predict the SC generation in a tapered optical fiber. The simulation can also be used for predicting the same in photonic crystal fibers or highly nonlinear fiber. We can predict the length of the tapering required for obtaining SC in different types of fibers. For these we need to know the various fiber parameters and also estimate the effective propagation constant of the fiber medium from where we can calculate the values of higher order dispersion terms. ❐

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