Optical Similariton Generation in Photonic Crystal Fibers

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Abstract – In this paper, we present a new method for continuum generation at 1.55 μm, exploiting the spectral characteristics of similaritons formation by Raman amplification in photonic crystal fibers. The continuum generated will be high powered, with a spectral density as flat as possible and it will cover the entire C band (1530 nm - 1565 nm). These properties will make it directly suitable for multi-wavelength optical applications.

Keywords- optical Similariton ; continuum source; Raman amplification; photonic crystal fiber.

I. INTRODUCTION

Continuum generation in optical fibers is one of the means to obtain broadband optical sources which can be used as transmitters in wavelength division multiplexing (WDM) systems. In this technique, short pulses are propagated in a fiber and under the nonlinear effects and the dispersion a broad spectrum is generated, which can then be sliced into different wavelengths or channels [1, 2, 3].

In the last few years, many researchers have focused on the generation of continuum sources in photonic crystal fibers (PCF) since the advent of this new type of guide in 2000 [4], owing to its high nonlinear coefficient. Another advantage of the microstructured fibers is their single mode characteristic over a wide wavelength range, allowing for a large spectral extension. This is not limited by the cut-off wavelength of the fundamental mode of the fiber. The dispersion of the fiber is also an important factor affecting the continuum generation dynamics [5, 6, 7]. When a pulse is propagated into the anomalous dispersion fiber, a broadened continuum is generated, but the coherence is not maintained. The continuum thus generated is also very sensitive to input pulses power fluctuations [8].

In the normal dispersion fiber, the nonlinear frequency chirp induced by self-phase modulation (SPM) interplays with the normal dispersion making the pulse waveform parabolic [1]. We can conclude that for telecom applications using a pulsed pump in normal dispersion fibers is preferable for continuum generation due to better coherence compared to the anomalous dispersion case. However the continuum thus generated had ripples due to the optical wave breaking [9] and its flatness was not maintained.

The first demonstration of parabolic pulses, or similaritons, was made by Fermann in the year 2000 [10], when he showed that the similariton is a result of the interactions between the normal dispersion, the non-linearity and the gain of the optical fiber.

Taking into account that the dispersion and the non-linearity coefficients are defined by the structural characteristics of the optical fiber, the only variables we could adjust to transform any propagating pulse into a similariton are its initial energy and the gain coefficient, or the amplification, of the optical fiber. Many studies, employing different amplification methods, Raman, Ytterbium or Erbium, in conventional fibers, have already proved the similaritons formation [11, 12, 13, 14].

Other studies were focused on the passive generation of similaritons by use of a normal dispersion decreasing dispersion fiber (ND-DDF). This is theoretically based on the solution of the Schrödinger non-linear equation in a non-amplifying medium having variable dispersion [15, 16, 17]. However this model showed limitations like higher order dispersion and high propagation losses degrading the self-similar evolution of the pulse after travelling on greater distances. It thus created the need for using a dispersion-decreasing fiber, potentially very expensive because of its difficult requirements, and made the benefits of using the passive technique less attractive.

Generally speaking, all studies mentioned earlier dealing with the generation of broadening and flat continuum source employed very long fibers, tens of kilometers in length, or alternatively higher power lasers. To lessen these constrains, we propose a new configuration which will enhance the spectral power.
and flatness of continuum sources by using as the propagation medium a normal dispersion photonic crystal fiber (PCF) and as the amplification method the Raman effect.

II. RAMAN AMPLIFICATION AND SIMILARITON FORMATION IN NORMAL DISPERSION PCFs

In our earlier work [18], we have numerically investigated the possibility to generate a flat and high power continuum by exploiting the formation of similariton pulses in a special highly nonlinear and low normal dispersion Photonic Crystal Fiber (PCF) with gain of amplification. Nevertheless, we did not appreciate on the nature of that amplification. In this paper we present how we can make use of Raman amplification in a normal dispersion PCF for continuum generation.

The numerical study begins with the standard choice of the parameters required for continuum generation. The employed laser and PCF characteristics must also be incorporated in the model. Additionally, the model for a Raman amplifier must also be integrated in our simulations. A realistic modeling of this medium is done using studies of Raman amplification already presented in the literature [19], [20]. In these, the net gain following Raman amplification is written as:

\[ G = \exp \left( \frac{g_R P_0 L_{\text{eff}}}{\Lambda_{\text{eff}}} - \alpha_s L \right) = \exp \left( \frac{g_R L_{\text{eff}}}{\Lambda_{\text{eff}}} - \alpha_s L \right) \]

(1)

\( L_{\text{eff}} \) and \( \Lambda_{\text{eff}} \) represent the effective length and area of the fiber, \( P_0 \) the optical power of the laser pump injecting in the fiber, and \( g_R \) the Raman gain coefficient in \( \text{m} \cdot \text{W} \). The peak value for this coefficient at a pump’s wavelength of \( \lambda = 1.45 \mu \text{m} \) is \( g_R = 7.6 \cdot 10^{13} \text{ m} \cdot \text{W} \) [20].

From equation (1) it can be noticed that the gain depends on the power of the pump and the characteristics of the fiber via its gain per unit length \( g_R = (g_k P_0)/A_{\text{eff}} \). Thus, in order to obtain an important amplification of the signal, one can act either on the power of the pump, or on the effective area of the fiber’s core. The latter is one of the reasons that the photonic crystal fibers were chosen in the first place.

It can be said that for the Raman amplification needed for similariton formation, one must use an optical fiber having the following characteristics:
- High non-linearity in order to have a fast broadening of the spectrum even when using a small power laser and a short fiber.
- Flat and small normal dispersion at the 1550 nm wavelength in order for the similariton maintains its power and parabolic shape.
- Small confinement losses and small effective area in order to optimize the amplification gain.

Because of these reasons, we have chosen the high non-linear fiber found in reference [21]. This PCF presents an ultra-flat normal chromatic dispersion of 4.0 ps / (nm-km) in the bandwidth going from 1.06 \( \mu \text{m} \) to 1.68 \( \mu \text{m} \). The confinement losses have a value of \( 10^{-1} \text{ dB} / \text{km} \) in the same bandwidth, a non-linear coefficient of 51.0 \([\text{W} \cdot \text{Km}]^{-1}\) and an effective area of 2.5 \( \mu \text{m}^2 \) for 1.55 \( \mu \text{m} \).

Figure (1) represents the variation of the gain as a function of the PCF’s length for different pump powers. It can be noticed that this gain directly depends on the power of the pump, which must be over a threshold value (in this case \( P_0 = 0.5 \text{ W} \) for a length of one meter) given by the following formula [19]:

\[ P_{th} \approx (\pi \cdot A_{\text{eff}} g_R L_{\text{eff}})^{1/2} \]

The gain thus increases with the length of the fiber until it reaches a maximum value of around 28 dB corresponding to a length of \( L = 150 \text{ m} \) for the case of 2 W of pumping power. The gain then decreases rapidly.

Our attention was then drawn onto the spectral widening of the newly formed similariton pulse. In this aim, the spectral widening can be characterized by following the evolution of the spectral width \( \Delta \lambda \) as a function of the fiber’s length. The spectral width \( \Delta \lambda \) can also be represented in frequency \( \Delta f \). The two quantities are linked by the following equation:

\[ \Delta f = \frac{1}{\pi} \left( \frac{g R E_{\text{ce}}}{2 \beta_2} \right)^{1/3} \exp \left( \frac{g L}{3} \right) = \frac{1}{\pi} \left( \frac{g R E_{\text{ce}} \log G}{2 \beta_2 L} \right)^{1/3} \]

(2)

Figure 2 presents the dynamics of the spectral widening for a laser pulse when the pump power is equal to 2 W, resulting in a gain per unit length of \( g_0 = 0.6 \text{ m}^{-1} \). It can be clearly seen that after around 30 m the spectral width of the similariton becomes \( \Delta \lambda = 78 \text{ nm} \), which is enough to cover the entire C-band used in WDM optical communications. That is why in the following simulations this length will be used to verify the validity of our numerical model.

![Figure 1: Variation of the Raman gain as a function of the PCF’s length for different powers of the pump](image-url)
To demonstrate the existence and to achieve the characterization of similariton pulses in the PCF, the initial pulse parameters are important. It is thus necessary to study the effect of these parameters on the evolution of pulses. This paper’s focus will be on the similariton dynamics for different initial energies. It has been proved that the pulses of various shapes and durations all converge to a similariton pulse with the same duration and amplitude [3]. Shorter initial pulses converge more quickly while the longer pulses require a longer distance for amplification.

Considering the equality between the dispersive fiber length \( L_D = T_0^2/|\beta_2| \) and the total fiber length, and considering that the pulses are exposed to sufficient dispersion, they can quickly become self-similar parabolic pulses by the interaction of the nonlinearity, normal dispersion and the gain. After the pulses evolve to similariton pulses, nonlinear length \( L_{\text{NL}} = 1/\gamma p_0 \) will rapidly decrease, and with the increase of \( L_D \), the evolution of self-similar pulses will accelerate.

In our case of equality between the \( L_D \) length and the PCF’s length, the input pulses’ duration must be of about 0.2 picoseconds.

Figure 3 shows the influence of the initial energy on the evolution of spectral and temporal widths of the initial pulse. From this figure it can be observed that the pulse widths are significantly increased with an increase of the initial energy. The output pulses are temporally and spectrally gradually expanded.

In order to use the highest possible pulse energy, this constraint will require that for an increase in the initial energy, the nonlinear length \( L_{\text{NL}} \) must become shorter; otherwise the excessive energy will bring a destructive effect on the linear chirp properties, resulting in the deterioration of the shape of the similariton pulse.

From Figure 3, it can also be seen that for a pulse with an initial energy of 1 \( pJ \), the pulses’ output duration will be of 8 ps and will have a spectral width of 78 nm. This is in fact, as seen earlier, the desired width for a continuum to span the entire C-band. For this reason we will chose this energy value in the following simulations to ensure the validity of our numerical model.

The numerical model that we have developed to modeling the propagation of similariton in the PCF is based on the nonlinear Schrödinger equation NLSE with gain [10]:

\[
\frac{\partial A}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - i \gamma |A|^2 A + g A
\]

In equation (3) \( A \) is the slowly varying amplitude of the pulse, \( \beta_2 \) is the second order dispersion of the fiber, \( \gamma \) is the nonlinear coefficient, and \( g \) is the gain coefficient.

Using the parameters of the proposed PCF fiber and the calculated linear gain \( g_0 \), and considering that the pulse profile to be introduced is of Gaussian shape, the electric field \( A(0, t) \) corresponding to such a pulse can be expressed in the following form:

\[
A(0, t) = \sqrt{P_0} \exp \left( -\frac{t^2}{2T_0^2} \right)
\]

In equation (4), \( P_0 \) is the power of the input pulse and \( T_0 \) is the temporal width. The temporal width is related to the full width at half maximum (FWHM) of the input pulse by FWHM = 1.665 \( T_0 \).

Our numerical simulation is based on the Split Step Fourier method, and it consists of taking into account the effects of dispersion and gain in the first half of a step, then the nonlinear effects in the second half [22].

The formation of similariton pulses in the gain medium can be further illustrated by plotting the temporal and spectral pulse shapes at the output of the PCF.

Figure 4a shows the time evolution of the pulses injected into 30 m of PCF, highlighting the reshaping of the pulse, followed by its self-similar evolution. The amplification gain was 18 dB which corresponds to a similariton pulse peak power of 100 W at the output of the PCF.

The characteristics of the similariton obtained after propagation into 30 m of PCF were then compared with those of the numerical simulations presented in Figure 3, noting the very good agreement.
between the two methods of simulation. This confirms the possibility for obtaining similarton pulses with the chosen values for the initial energy $E (= 1 \mu J)$, gain of amplification $g_0 (= 0.6 \text{ m}^{-1})$, and for the length of the PCF ($L_{\text{PCF}} = 30 \text{ m}$).

In addition to illustrating the similarton pulse generation by an active propagation of the initial pulse into the PCF, these simulations also show the possibility for great spectral widening by self-similar expansion. Specifically for an initial wavelength of 1550 nm, a continuum source with a spectral bandwidth of about 80 nm is produced (Figure 4.b), with good flatness in the middle of the spectrum. The small ripples seen in the middle of the spectrum are the result of the interference between the identical optical frequencies in the pulse.

![Figure 4](image)

**Figure 4:** Temporal (a) and spectral (b) evolution of a similarton in the amplifying PCF

### III. Conclusion

We have investigated a new continuum generation method based on similarton formation in photonic crystal fibers using the Raman effect as a mean for amplification. The resulting continuum is high-power and spectrally wide and flat in the entire C-band of optical communications. The future practical realization of such a continuum would represent a great advance in a range of applications, such as generation of multiwavelength sources for WDM systems. This can be done by spectral slicing of the resulting continuum. From a single light source it will be thus possible to generate many identical optical channels with different wavelengths, having the same properties as the original source. The advantage in terms of costs could prove significant.

### REFERENCES


