Flat and broadband Continuum source based on similariton spectrum generated in germanium-doped photonic crystal fiber for DWDM

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***Abstract*— We investigate the generation of flat and broadband Continuum based on similariton spectrum in germanium-doped photonic crystal fiber via Raman amplification. The proposed fiber is analyzed numerically using vector Finite Element Method (VFEM) with a circular perfectly matched layer (PML). By using 30 mol% of germanium concentration, we obtain ultra-high nonlinearity about 61.71w^{-1}km^{-1}, low confinement loss about 2.42*10^{-8} dB/km and near zero flattened normal chromatic dispersion of -2.55 ps/nm/km from 1450 to 1650nm. The continuum generated into the 3.5-m-long proposed fiber has flat and broadband spectrum of 130 nm and centered at 1550nm. This continuum allows generating at least 100 channels separated by 100 GHz for DWDM.**

Keywords*— *Continuum, Similariton, photonic crystal fiber, germanium doped- fiber, Raman amplification, DWDM.

I. Introduction

Self-similar parabolic pulse generation in optical fiber amplifier often referred to as a Similariton pulse, has many notable advantages, such as: high repetition rate, wide spectrum with low spectral ripple, and high peak power. This new class of optical pulse is of interest considerable for many applications, such as: optical regeneration for high bit rate telecommunications signals and Wavelength Division Multiplexing (WDM) [1]. The conventional WDM transmitter contains a set of lasers diodes emitting at different wavelengths. However, such transmitter requires a precision temperature control to eliminate the center wavelength drift. The generated continuum based on similariton spectrum could be used as a source of multi-wavelength adapted to WDM where intensity and spectral flatness are of considerable importance.

In this work, we analyze numerically with the vectoriel Finite Element Method (FEM) a photonic crystal fiber (PCF) based on germanium-doped silica material with different concentrations (0 mol%, 15 mol% and 30 mol%) in order to achieve high nonlinearity, flat and low normal dispersion. Next, we generate in this fiber via Raman amplification a continuum based on similariton spectrum covering C, L bands.

II. Simulation Model

The design of the proposed fiber consists of seven rings of circular air holes arranged in a hexagonal lattice. Fig. 1 shows the cross-section of proposed PCF. The material is germanium doped silica with different concentrations. The main-hole diameters from inside to outside are d_1, d_2, d_3 and d respectively. The pitch Λ is distance between two air holes. By tuning these parameters and using the background material as silica with different concentrations of germanium 0 mol%, 15 mol%, 30 mol%, we control dispersion and nonlinear coefficient of the fiber around desired wavelengths.

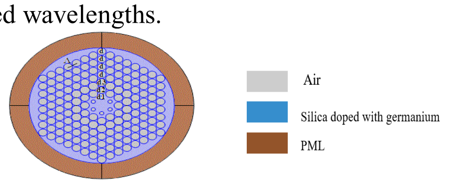


Fig1: Cross section of proposed PCF with Λ= 0.87µm, d_1=0.385 µm, d_2 = 0.79µm, d_3= 0.88µm and d = 0.79µm.

The Refractive index of Ge-doped silica is given by the Sellmeier dispersion equation [2]:

$$n^2(\lambda) - 1 = \sum_{j=1}^{3} \frac{[SA_i + X(GA_i - SA_i)]\lambda^2}{\lambda^2 - [Sl_i + X(Gl_i - Sl_i)]^2} \quad (1)$$

Where n is the refractive index of Ge-doped silica, SA_i, Sl_i, GA_i, and Gl_i are the Sellmeier coefficients for the SiO_2 and GeO_2 glasses respectively and X is the GeO_2 concentration in mol%. After the calculation of effective index of the fundamental mode (HE_{11}) using the FEM, the dispersion, nonlinear coefficient and confinement loss parameters can be obtained.

The similariton is result of interaction between normal dispersion, nonlinearity and gain. The dispersion can be calculated by the following equation [3] :

$$D_{ch}(\lambda) = -\frac{\lambda}{c}\frac{d^2\Re e(neff)}{d\lambda^2} \quad (2)$$

Where λ is the operating wavelength, c is the speed of light in vacuum, $Re\ (neff)$ is real part of the effective index of fundamental mode.

The nonlinear coefficient can be expressed as:

$$\gamma(\lambda) = \frac{2\pi n_2}{\lambda A_{eff}} \quad (3)$$

Where n_2 is non-linear refractive index of Ge-doped silica that is given by $(2.16 + 0.033X) \times 10^{-20}$ m^2/W [4]. The effective mode area is given by:

$$A_{eff} = \frac{(\iint |E|^2\, dxdy)^2}{\iint |E|^4\, dxdy} \quad (4)$$

Where E is the transverse component of the electric field.

Light confinement is the ability of the PCF to confine light inside the core region. The Confinement loss is expressed in dB/Km[3] by the following expression:

$$L = 8.686 * \left(\frac{2\pi}{\lambda}\right) * Im(n_{eff}) \quad (5)$$

Where Im (n_{eff}) is imaginary part of the effective index of fundamental mode.

III. SIMILARITON GENERATION

The mathematical model of the *Similariton* generation is described by the nonlinear Schrodinger equation (NLSE) [4]:

$$i\frac{\partial E}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2} - \gamma|E|^2 E + i\frac{g}{2}E \qquad (6)$$

Where β_2 is GVD parameter and g is the Raman gain (in m^{-1}) defined by :

$$g = P_{pum}.g_R/A_{eff} \qquad (7)$$

Where P_{pum} is injected pump power and g_R is the Raman gain coefficient that is related to the imaginary part of the Fourier transform of $h_R(t)$ as [5]:

$$g_r(\omega) = 2\,\gamma\, f_r\, Im\,[h_R(\omega)] \qquad (8)$$

Where h_R (ω) is the Fourier transform of the temporal Raman response function, f_r represents the fractional Raman contribution and it is taken $f_r = 0.18$. The Raman response function $h_R(t)$ can be approximated:

$$h_R(t) = \frac{{\tau_1}^2 + {\tau_2}^2}{\tau_1 {\tau_2}^2} e^{\frac{-t}{\tau_2}} \sin\left(\frac{t}{\tau_1}\right) \qquad (9)$$

For GeO_2-doped glass fiber τ_1=11.9 fs and τ_2=65 fs[5].

IV. SIMULATION AND RESULTS

Figure 2 shows the dispersion profile of proposed PCF (Λ=0.87µm, d_1=0.385 µm, d_2=0.79µm, d_3=0.88µm, d=0.79µm) for pure silica and different germanium doping concentrations. For germanium doped PCF with concentration 30 mol% we arrive to obtain the dispersion equal to -2.55ps/(km-nm) and flattened from 1450nm to 1650 nm.

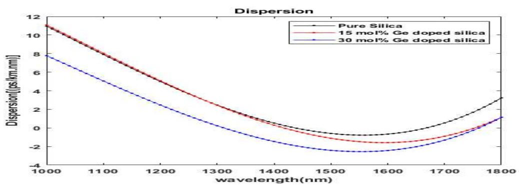


Fig. 2: The Chromatic Dispersion of proposed fiber with different concentrations of germanium.

Figure3 illustrates that the nonlinear coefficient increases with increasing germanium doping. By using 30mol% Ge doping the PCF possess high nonlinearity around (61.71$w^{-1}km^{-1}$) at 1550 nm.

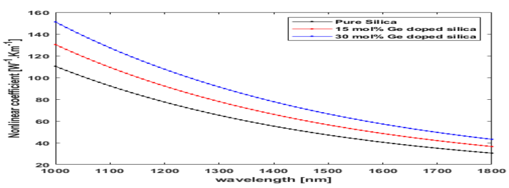


Fig.3: The nonlinear coefficient of the proposed fiber with different concentrations of germanium

Figure 4 shows very low confinement loss of $0.00242*10^{-5}$ dB/km at the operating wavelength of 1550 nm using 30 mol % of germanium concentration.

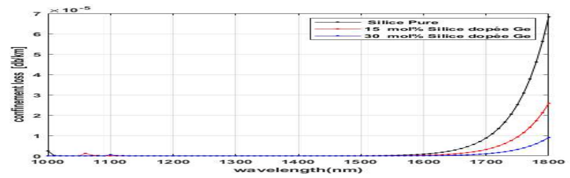
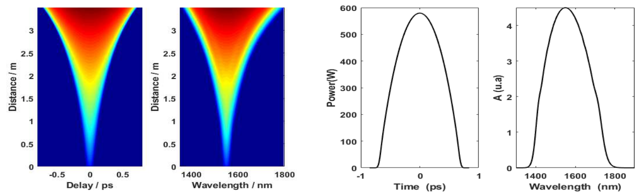


Fig. 4. Confinement loss in proposed fiber with different concentrations of germanium.

We have simulated the propagation of a Gaussian pulse having an initial duration of 0.1 ps and an initial peak power P_{pum}= 4w in the optimized fiber with Raman gain coefficient g=2 m^{-1} by the resolution of equation(6) by split step Fourier method (SSFM). We generated at the output of 3.5m of this fiber the Self-similar parabolic pulse that temporal and spectral profiles are presented in fig.5. The generated similariton has a broadband spectrum that shows good spectral flatness (very low power variation ±0.9dB) over a range of 130 nm covering the C,L bands (fig.6). This continuum allows generating at least 100 channels separated by 100 GHz after spectral slicing by optical demultiplexer for DWDM system.



(a) (b)

Figure.5 a. Spatiotemporal and spatiospectral evolution of the generated similariton in designed fiber. b. Temporal and spectral profile of Self-similar parabolic pulse at 3.5m of designed PCF.

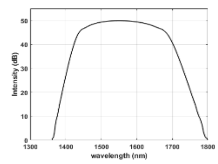


Fig.6.Similariton spectrum at output of 3.5 m of designed PCF

V.CONCLUSION

We have generated a similariton spectrum (continuum) into 3.5-m-long germanium doped photonic crystal fiber with 30 mol % of concentration via input power of 4w and Raman Amplification. The obtained continuum is ultra-flattened over 130 nm covering the C,L bands. This continuum could be applied as multichannel source for DWDM system to achieve high capacity transmission.

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