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Dispersion tailoring in single mode optical fiber by doping silver nanoparticle

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Abstract We propose an optical fiber which has very low dispersion loss (typically $\sim$ 6.7 ps^2/km at 1,550 nm) that can be achieved by doping Ag nanoparticle into the core glass. At low absorption loss approximation, dispersion free propagation can be achieved up to 64 km for a 20 ps pulse. Enhanced third order nonlinearity due to the presence of Ag nanoparticle (typically $\sim 3.82 \times 10^{-20}$ W/m^2) compensates for long length dispersion broadening that is not possible in conventional fused silica step index fiber.

1 Introduction

In optical communication network dispersion limits the propagation distance. It limits the maximum bit-rate of the signal and effective length of propagation. For this reason dispersion compensator is needed after a few kilometers of interval to restrict the pulse broadening occurred due to dispersion and also the attenuation loss is compensated by gain block [1]. Normally dispersion compensating fibers are used to overcome these difficulties which are expensive as well as lossy [2]. Ytterbium (Yb) doped optical fiber are also used to compensate group velocity dispersion (GVD) [3–7]. The main principle behind dispersion compensation in the Yb doped fiber is to use the high nonlinearity of the fiber to compensate the GVD. The nonlinear refractive index of an Yb doped fiber is very high. If the input power is large then self phase modulation (SPM) efficiently reduces the dispersion broadening of the optical pulse, but if the nonlinearity starts dominating over dispersion then pulse would start disintegrating. A good balance between nonlinearity and dispersion is needed for efficient dispersion compensation. In most of the cases conventional single mode fiber (SMF) is spliced with Yb doped fiber for this reason as was done in Ref. [5]. The GVD value of SMF balances the high nonlinearity of the Yb fiber [5]. In an optical fiber laser cavity high power builds up and this high power enhances the nonlinearity of the fiber [3, 4, 6]. As reported in one case the power builds up in the cavity is around 300 mW. This high power generates large nonlinear index inside the doped fiber and thus GVD can be compensated. This type of compensation is efficient and can restrict broadening due to dispersion of ultrashort pulses, but these techniques may not be suitable for dispersion compensation in long length optical communication network. The signal power used in communication system is very low. So the optical fiber is required to produce a large nonlinearity even at low power in order to compensate dispersion. Laser cavity cannot be placed within a communication channel due to its complex mode of operation. Hence the use of Yb doped fiber for dispersion compensation in communication system may not be a possible solution. The present study demonstrates a step index fiber where the second order dispersion can be tailored and large nonlinearity can be produced even at very low power (typically 30 nW) by doping silver nanoparticle in the core glass. An optimization on the size and volume fraction for spherical silver (Ag) nano-particle (NP) is attempted for dispersion tailoring of a step index single mode fiber. First the composite material i.e. Ag nano-particle embedded fused silica is studied where the effective medium approach is taken into consideration to optimize the optical properties of the composite. The size of the doped Ag nano-particle (10 nm) are very small compared to the operating wavelength (1,550 nm) and from Mie

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scattering theory it can be shown [8, 9] that absorption will dominate over scattering. So an optical signal with large wavelength compared to the radius of the nanoparticle would mostly be absorbed rather being scattered. Hence the said composite glass can be used to guide optical wave. Subsequently ps (pico second) pulse propagation through a single mode step index fiber is studied in order to compare the results with Ag-NP doped fiber.

2 Theoretical modeling

As the core of the fiber is based on Ag-NP composite it is useful to study various methods to find out the permittivity of a composite material where metal nanoparticles are embedded in a dielectric medium, in the present case it is high purity silica glass. The methods are Maxwell–Garnett theory, Bruggemann theory of effective medium and Sheng's granular microstructure theory. Depending on the structural geometry of the composite and also the spatial distribution and homogeneity of the doped particles one of the effective medium approaches should be followed. EMT (Effective Medium Theory) describes composite mixtures in terms of ε_{eff} and μ_{eff}, in quasi-static limit. The static solution considers the potential around one inclusion of permittivity ε_i. In EMT the scale of inclusions is assumed to be much smaller than the electromagnetic wavelength in the host material (ε_h). In addition, the mixture must be homogeneous on a macroscopic scale. The particle distribution is considered random, so that for any region of a scale on the order of the wavelength in the host, there is a constant volume fraction '*f*' of inclusions [10].

The effective permittivity of the composite material according to MG model is given by

$$\frac{\varepsilon_{\text{eff}} - \varepsilon_2}{\varepsilon_{\text{eff}} + 2\varepsilon_2} = f\frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_{\text{eff}}} \tag{1}$$

Detail calculation and assumptions are given in Appendix.

In order to estimate variation in the dielectric permittivity of a metal nanoparticle in comparison with that of a bulk sample, we use a classical model taking into account the limitation in the electron free path length due to its collision with the particle boundary. According to this model the permittivity of the silver nano-particle is [11]

$$\varepsilon(\omega) = \varepsilon_{¥} - \frac{\omega_p^2}{\omega^2 + i\omega/\tau_f} - \frac{f_1\omega_0^2}{\omega^2 - \omega_0^2 + i\omega/\tau_b} \tag{2}$$

where, ω_P is the plasmon resonance frequency of the metal, τ_f, given by $1/\tau_f = 1/\tau_0 + v_f/R_1$ is the relaxation time, ω is the frequency of interest and *i* is the complex number, $i = \sqrt{-1}$. The contribution from interband transitions at infinite frequency (that is, the static contribution) is $\varepsilon_{¥}$. The new Lorentz term includes the Lorentz oscillator damping time τ_b, ω_0 is the Lorentz resonance width and f_1 is the weighting factor. v_f is the Fermi velocity of the metal and R_1 is the radius of the metal nano-particle. The values of different parameters are taken according to Ref. [11] as shown in Table 1.

The permittivity of the fused silica is calculated from the empirical relation [1].

$$\sqrt{\varepsilon_2(\lambda_0)} = C_0 + C_1\lambda_0^2 + C_2\lambda_0^4 + \frac{C_3}{(\lambda_0^2 - 1)} + \frac{C_4}{(\lambda_0^2 - 1)^2} + \frac{C_5}{(\lambda_0^2 - 1)^3} \tag{3}$$

where $C_0 = 1.440854$, $C_1 = -0.0031268$, $C_2 = -0.0000381$, $C_3 = 0.0030270$, $C_4 = -0.0000779$, $C_5 = 0.0000018$, $1 = 0.035$. λ_0 is the wavelength measured in micrometer.

The difference between the values of refractive indices of the composite materials as calculated from Maxwell–Garnett (MG) and Brugemann (S-BG) theories occurs due to the assumption involved in deriving the two formulae. In MG theory the doped particles are assumed to exist in mono-dispersed form and the host medium is taken as uniform whereas in S-BG both the doped particle and the host medium are considered in dispersed phase. So when metallic inclusion is considered the two formulations take different forms, which are calculated and shown in Figs. 1 and 2.

Now let us consider the case of Ag-NP doped optical fiber. The distribution of particle is considered uniform and axially symmetric in the core region of the optical fiber. Due to the cylindrical symmetry the effect of second order non-linear susceptibility can be neglected. Third order non-linearity of the composite core material is studied considering the real effective applications such as restricting the dispersion associated with the propagating pulse. The third order susceptibility of Ag-NP doped glass according to MG theory is given by [12] (Fig. 3)

$$\chi_{\text{eff}}^3 = f\frac{\chi_m^3}{|P|^2P^2} + \frac{\chi_h^3\{1 - f(0.4[4|\sigma|^2\sigma^2 + (3|\sigma|^2\sigma + \sigma^3) + 9(|\sigma|^2 + \sigma^2)])\}}{|1 - \sigma f|^2(1 - \sigma f)^2} \tag{4}$$

where $P = (1 - \sigma f)\frac{\varepsilon_m + 2\varepsilon_h}{3\varepsilon_h}$, σ is defined by Eq. (10.b), χ_m^3 and χ_h^3 are the third order susceptibility of the silver and glass respectively [12]. Hence the intensity dependence refractive index for the material is given by $n_2 = \frac{3\chi_{\text{eff}}^3}{4\varepsilon_0\varepsilon_{\text{eff}}c}$, ε_0 is the free space permittivity and c is the velocity of light in vacuum. The values of χ_m^3 and χ_h^3 are taken from Ref. [12, 13].

It is to be noted from Eq. (4) that the MG model is strictly valid only in the limit of small fill fractions, that is, for $f \ll 1$. The reason for this restriction is that for a dense

Table 1 Drude-Lorentz parameter for Silver (Ag)

Metal	ε_∞	ω_p (rad/s)	τ_0 s^{-1}	ω_0 (rad/s)	f_1	τ_b s^{-1}
Silver	3.7187	1.396×10^{16}	3.29×10^{-14}	6.496×10^{15}	0.4242	1.697×10^{-16}

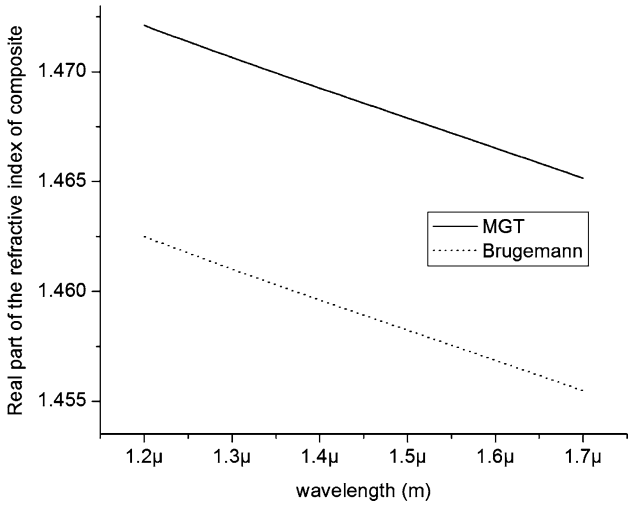

Fig. 1 Variation of refractive index of the composite material with wavelength for $f = 0.01$ and $R_1 = 10$ nm. (1) real part of index, (2) imaginary part of index

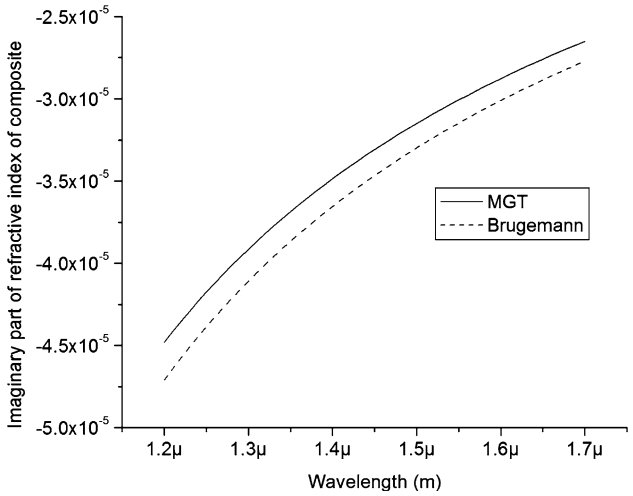

Fig. 2 Variation of refractive index of the composite material with wavelength for $f = 0.01$ and $R_1 = 10$ nm. (1) real part of index, (2) imaginary part of index

collection of doped particles, the polarization induced in a given particle depends on the average electric field in the material and also on the dipole fields of its neighboring particles. This latter contribution is not properly accounted for in MG formulation of the linear as well as the nonlinear response behavior. Although the limit of validity is strictly for $f \ll 1$, the MG model can be applied for fill factors up to 0.5, above which these correlations between the polarizations of neighboring particles become dominant [14]. We may consider solution doping technique to fabricate this kind of composite which may satisfy the above assumption of MG theory.

As we have mentioned fiber dispersion plays a critical role in propagation of short optical pulses because different spectral components associated with the pulse travel at different speeds given by c/n(ω). Even when the nonlinear effects are not important, dispersion-induced pulse broadening can be detrimental for optical communication systems. In the nonlinear regime, the combination of dispersion and nonlinearity gives a qualitatively different behavior. For pulses of long duration ($T_0 > 100$ ps) the effect of dispersion is not significant as the dispersion length $L_D = T_0^2/|\beta_2|$ ($\beta_2 =$ GVD) is much larger than the length of the fiber. When the pulse duration $\sim$ 10 ps then this dispersion length becomes comparable with the fiber length and starts contributing in pulse broadening [15, 16]. It was experimentally observed that an optical fiber with negative dispersion coefficient causes pulse narrowing [17]. The group velocity and GVD are given as [16]:

$$\beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c}\left(n + \omega \frac{dn}{d\omega}\right) \tag{5.a}$$

$$\beta_2 = \frac{1}{c}\left(2\frac{dn}{d\omega} + \omega \frac{d^2n}{d\omega^2}\right) \tag{5.b}$$

where n_g is the group index and v_g is the group velocity. The parameter β_2 represents dispersion of the group velocity and is responsible for pulse broadening. The variation of β_2 with wavelength in fused silica and the composite material is given below for different f values.

In order to achieve dispersion minimized propagation it is desirable that the material of the optical waveguide should have a nearly zero GVD at the operating wavelength for communication. Generally 1,550 nm is used in majority cases of communication network. Hence an optimization study has been carried out to examine whether a zero or nearly zero GVD parameter can be achieved for the proposed composite material of the core glass. Assuming the doped Ag nano-particle spherical in nature the radius and the filling factor is varied over a range to study their effect on the GVD at 1,550 nm. The optimization plots are shown in Fig. 5. The optimization study indicates that at particle size of 10 nm and with 0.013 filling factor a nearly zero GVD can be attained at 1,550 nm in the proposed fiber. For fused silica GVD is zero at 1,270 nm.

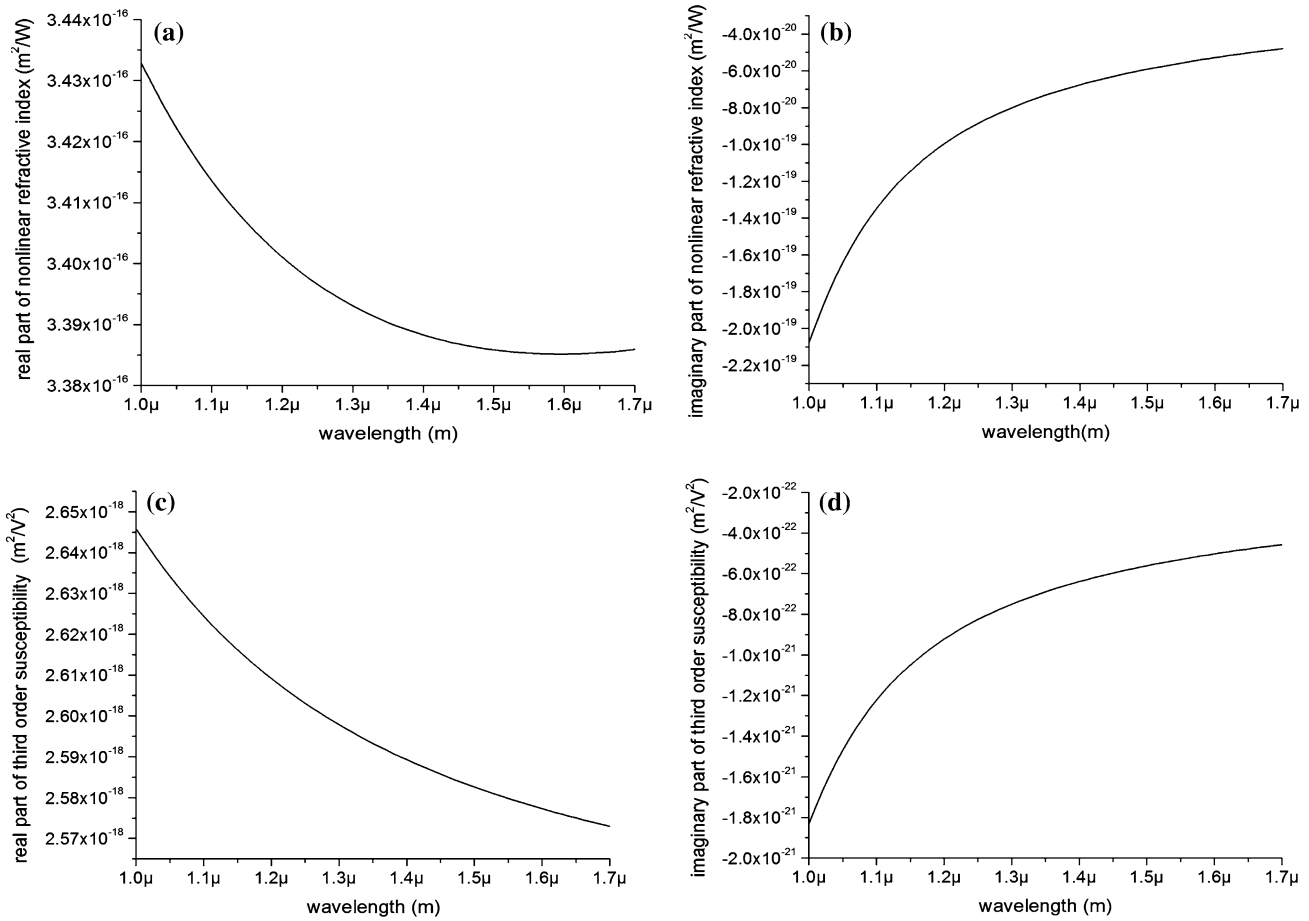

Fig. 3 **a**, **b** Non-Linear refractive index of the composite material. **c**, **d** Third order susceptibility of the composite material. $f = 0.01$, $R_1 = 10$ nm

Taking into consideration the feasibility of manufacturing technique of such kind of composite fiber the Ag particle size has been chosen to 10 nm and the filling factor is taken about 0.01 or 1 % in volume fraction.

3 Pulse evolution

The evolution of a pulse (width, $T_0 > 5$ ps) in optical waveguide is governed by the equation [16]

$$i\frac{\partial A}{\partial z} + i\alpha A - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} + \gamma|A|^2 A = 0 \tag{6}$$

where $A(z, t)$ is a slowly varying pulse envelope, α is the absorption coefficient and $\gamma = \frac{n_2\omega_0}{cA_{\text{eff}}}$is the non-linear parameter, n_2 is the non-linear refractive index A_{eff} is the effective core area. For a single mode fiber it can be taken equal to the fundamental mode area. The input signal is taken as,

$$A(z,T) = P_0\exp(-\alpha z)U(z,T) \tag{7.a}$$

where

$$U(0,T) = \exp\left(-\frac{(1+\text{iC})}{2}\frac{T^2}{T_0^2}\right) \tag{7.b}$$

C is called the chirped parameter.

At $\alpha = 0$ in Eq. (6) is known as the non-linear Schrodinger equation. This equation shows the combined effect of GVD and nonlinearity of the fiber simultaneously on the input pulse. A nonlinear length L_{NL} is defined as $(\gamma P_0)^{-1}$. When the fiber length $L \ll L_{\text{NL}}$ and L_{D} the effect of dispersion and nonlinearity is negligible. This condition is satisfied for communication fibers when $T_0 > 100$ ps. In the condition $L \sim L_{\text{D}}$ and $L_{\text{NL}} \gg L_{\text{D}}$ only dispersion broadening of input pulse occurs and if L $\sim$ L_{NL} and $L_{\text{D}} \gg L_{\text{NL}}$ spectral broadening of the input pulse takes place. When $L \sim L_{\text{D}} = L_{\text{NL}}$ the effect for both nonlinearity and dispersion becomes prominent. Split step Fourier Transform is a standard method to solve Eq. (6). For an initially unchirped

Gaussian pulse, dispersion induced broadening of the pulse does not depend on the sign of the GVD parameter β_2. Thus, for a given value of the dispersion length L_D, the pulse broadens by the same amount in the normal and anomalous dispersion regions of the fiber. This behavior changes if the Gaussian pulse has an initial frequency chirp. The instantaneous frequency increases linearly from the leading to the trailing edge (up-chirp) for $C \gg 0$ while the opposite occurs (down-chirp) for $C \ll 0$. [16]

Taking $\alpha = 0$ Eq. (6) is solved for step index single mode fused silica fiber and also for step index single mode fiber where the core is made of the composite material. The evolution of a 20 ps unchirped Gaussian pulse with peak power 30 nW for both cases is shown in Fig. 6.

For a standard SMF-28 fiber the values of n_2 and β_2 are 2.53×10^{-16} m^2/V^2 and 21.3 ps^2/km respectively [18]. In the present study value of $N = 1.6$ $\left(N = \frac{L_D}{L_{NL}}\right)$ can be achieved for composite fiber with $P_0 = 1$ μW of input power, but for SMF fiber the value of P_0 becomes as high as 40 mW. Present study shows that for SMF-28 with input power of 40 mW dispersion compensated propagation is possible up to 17 km but for the composite fiber it is 64 km with input power as low as 30 nW.

4 Discussion

The study shows that the composite material has some advantages over fused silica. Firstly the refractive index can be manipulated over a wide range of value than fused silica. Secondly the GVD can be tailored from negative value to positive value only by changing the Ag particle concentration and for a fixed radius. Also GVD can be manipulated by changing the size of the Ag particle (Figs. 4, 5). These advantages of the composite material help to achieve an optical fiber with very low value of GVD. From the comparative study as shown in Fig. 6 it is evident that fiber made of such composite can support a

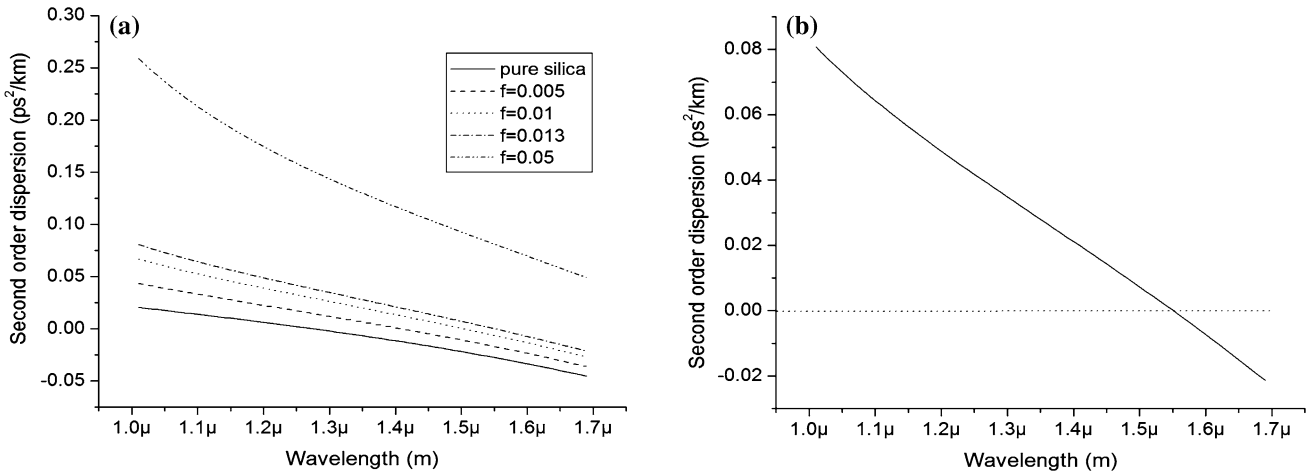

Fig. 4 Variation of β_2 with wavelength **a** for different filling factor (f), **b** for the composite material for $f = 0.013$

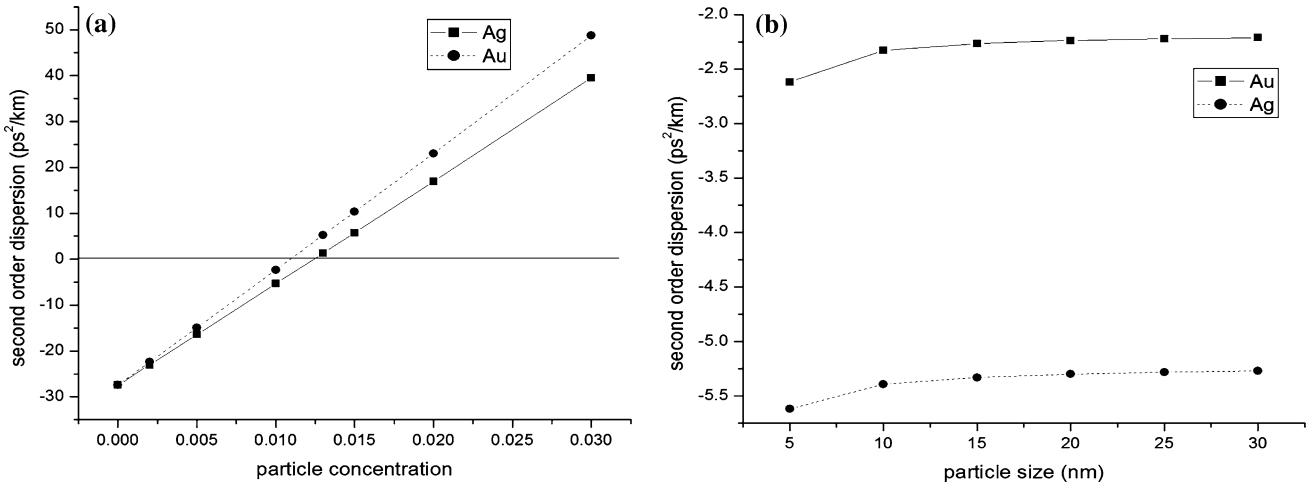

Fig. 5 Variation of β_2 with **a** particle concentration, **b** particle size

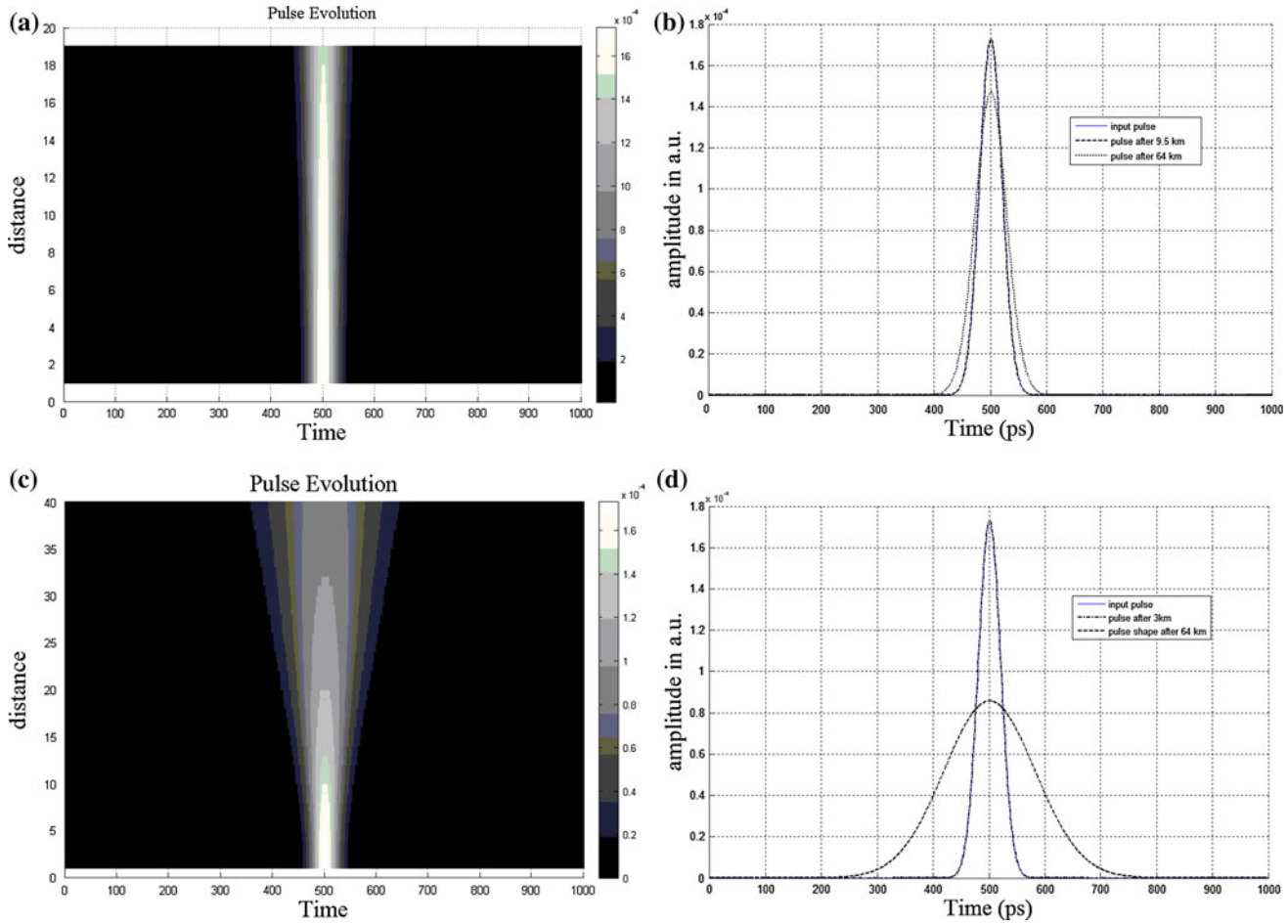

Fig. 6 Evolution of pulse **a** in composite fiber **c** in fused silica fiber for a propagation length of $z = 64$ km. (distance measured in $L_d = T_0^2/|\beta_2|$). Pulse shape after three different propagation length **b** composite fiber **d** fused silica fiber. $\lambda = 1{,}550$ nm

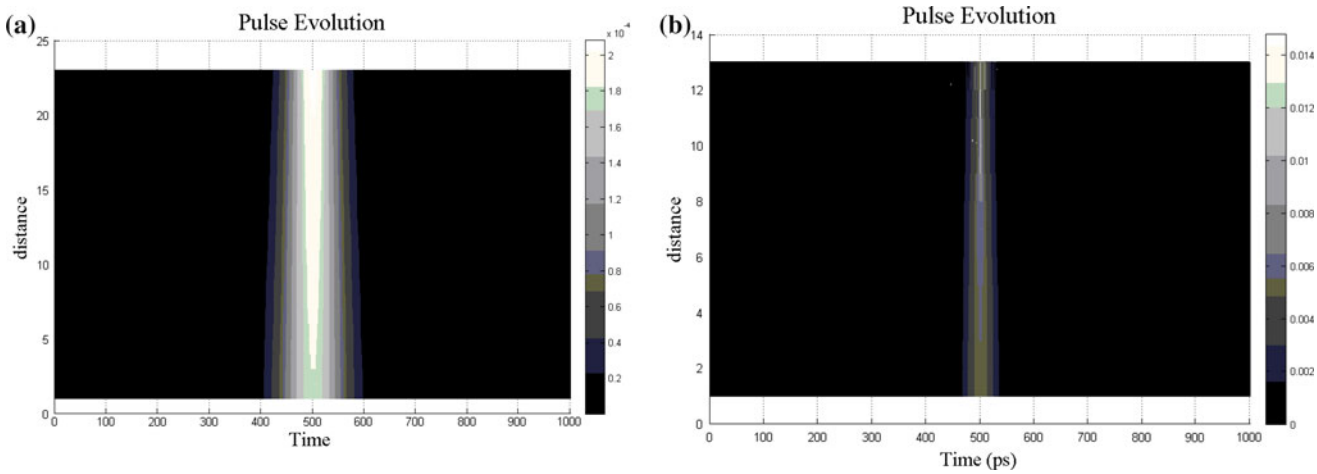

Fig. 7 Pulse evolution in non-linear composite fiber for different pulse duration and pulse peak power. $C = -2$, $\lambda = 1{,}550$ nm. **a** $T_0 = 50$ ps, $P_0 = 30$ nw, $L = 20$ km, **b** $T_0 = 20$ ps, $P_0 = 30$ μw, $L = 8$ km

long propagation with negligible broadening of input signal pulse. We observed that the pulse shape remains unchanged for 64 km propagation length in the composite fiber, whereas for a fused silica fiber the pulse retains its shape over a length of 8 km only if the absorption loss is considered to be zero for a pulse of 20 ps. Figure 7 gives a

comparative results of pulse width and peak power of chirped Gaussian pulse propagation. A pulse squeezing is observed for a chirped 50 ps Gaussian pulse with C = −2. The length of the fiber taken to be 20 km and input pulse power is 30 nW. When the pulse width is reduced to 20 ps and power is increased to 30 μW, same result is obtained at a shorter length i.e. at 8 km.

5 Conclusion

The present study shows advantages of silver doped fiber over conventional fused silica and other doped fibers. The high value of nonlinearity and low dispersion value make this fiber suitable for long length communication even though the pulse width >5 ps. These benefits can be achieved through special kind of optical fiber such as Photonic Crystal Fiber, but there are disadvantages too. Hence the proposed new kind of fiber with better propagation characteristics at 1,550 nm suitably counters the dispersion.

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Appendix

All the three models have certain merits and demerits. When the doped metal particle concentration is low all three theories give similar result [10]. But when the concentration increases the Maxwell–Garnett (MG) theory becomes inaccurate as the metal particles could form a connected network in the host matrix which is not considered in the formulation. However Sheng's model is valid when both the host and dopant are granular in nature, which does not satisfy since we consider metal particle that are doped uniformly in host matrix of silica, which is not granular in nature [19]. In such case Bruggemann's (BG) effective medium theory is useful to calculate the permittivity of the composite structure. We have taken spherical metal particles doped in silica as dielectric medium. It can be shown that if a particle of permittivity of ε_1 is embedded in a homogeneous medium of permittivity ε_2 then effective permittivity ε_{eff} of such a composite becomes [20]

$$f\left(\frac{\varepsilon_1-\varepsilon_{\text{eff}}}{\varepsilon_1+2\varepsilon_{\text{eff}}}\right)+(1-f)\left(\frac{\varepsilon_2-\varepsilon_{\text{eff}}}{\varepsilon_2+2\varepsilon_{\text{eff}}}\right)=0 \tag{8}$$

where f is the nanoparticle filling factor given as $f = V_{\text{Ag}}/V_{\text{total}}$. For small filling factor $f \ll 1$, $\varepsilon_{\text{eff}} \approx \varepsilon_2$ and $\varepsilon_{\text{eff}} + 2\varepsilon_2 \approx 3\varepsilon_{\text{eff}}$. Under this approximation, the above equation is identical to Maxwell–Garnett equation [12]

$$\frac{\varepsilon_{\text{eff}}-\varepsilon_2}{\varepsilon_{\text{eff}}+2\varepsilon_2}=f\frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1+2\varepsilon_{\text{eff}}} \tag{9}$$

Since the doping of Ag nano-particle in glass host is considered to be very low (around 1–2 % volume concentration) in the present case Maxwell–Garnett theory is adopted. From Eq. (9) we get

$$\varepsilon_{\text{eff}}=\varepsilon_2\frac{1+2\sigma f}{1-\sigma f} \tag{10.a}$$

where

$$\sigma=\frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1+2\varepsilon_2} \tag{10.b}$$

Equation (10.a) a, b can be used to find out the effective permittivity of the composite material. Hence the refractive index of the material can be found out from the relation $n=\sqrt{\varepsilon_{\text{eff}}}$. In this study ε_1 denotes the permittivity of the silver nano-particle and ε_2 denotes the permittivity of the fused silica. Jordi Sancho-Parramon et al. [21] used the MG formulation to describe the experimental reflectance data of a silver-glass composite film.

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