Indian J. Phys. **80** (5), 523-526 (2006)

IJP

Damping effect on power loss in optical fibers due to higher order nonlinear term

Sunita Sharma*, S K Ghoshal and Devendra Mohan
Guru Jambheshwar University, Hisar-125 001, Haryana, India

E-mail : Sun_phy2003@yahoo.com

Abstract : The nonlinear response of optical fiber based on anharmonic oscillator model is investigated analytically and numerically. The response of the fifth order nonlinear refractive index with the frequency of LASER at 1.33μm is examined. The present work is motivated from a number of theoretical and experimental studies on power loss in optical fiber. The power loss due to imaginary part of fifth order nonlinear refractive index for Pure Silica Core Fiber, Dispersion Shifted Fiber and Dispersion Compensating Fiber is calculated. The variation of power loss with damping constant is also calculated at 2 mW . We find a finite contribution due to fifth order anharmonic term. Controlling such nonlinearity is very important for technological applications.

Keywords : Anharmonic oscillator model, susceptibility, refractive index, damping factor.

PACS Nos. : 42.65.-k, 42.81.-i

1. Introduction

The response of any dielectric with electromagnetic wave becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception. On a fundamental level, the origin of nonlinear response is related to anharmonic motion of bound electrons under the influence of the applied field, if the external field is strong enough to distort the internal dipole field. So, the induced polarization P from the electric dipoles is not linear in the electric field E, but satisfies the relation;

$$P = \varepsilon_0[\chi^{(1)}.E + \chi^{(2)}.E^2 + \chi^{(3)}.E^3 + ---] \quad (1)$$

where ε_0 is the vacuum permittivity and $\chi^{(j)}$ (j = 1, 2,--) is the j-th order susceptibility. The linear susceptibility $\chi^{(1)}$ represents the dominant contribution to P. Since SiO_2 is a symmetric molecule, $\chi^{(2)}$ vanishes for silica glasses. As a result optical fibers do not normally exhibit second-order nonlinear effects. Nonetheless, the electric-quadrupole and magnetic-dipole moments can generate weak second-order nonlinear effects. Defect or color centers inside the fiber core can also contribute to second harmonic generation under certain conditions [1]. Materials that exhibit strong nonlinearity of refractive index are suitable conditions for applications in optical switching devices [2]. The imaginary part of refractive index (n) is a convenient way of expressing the loss term. This loss is due to γ (damping factor) which originates due to complex interaction of Si and O atom with external electromagnetic field. The Kerr nonlinearity originates from third order non-resonant electronic susceptibility and Raman susceptibility. Electrostriction is the process in which the material density increases in response to the intensity of an applied electromagnetic field creating a proportional change in the refractive index of the material [3]. The power loss in optical fibers due to Kerr and Electrostrictive nonlinear effects at 1.55 μm is studied extensively in recent years [4].

2. Model calculation

The origin of nonlinearity is the non-resonant electronic response. In anharmonic oscillator model, the equation of motion of the displaced electron as a forced harmonic oscillator is represented by :

*Corresponding Author

$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x + Dx^2 + Gx^3 + Fx^5 = (eE_0/2m).(e^{i\omega t} + e^{-i\omega t}), \quad (2)$$

where γ is the damping factor, e is electronic charge, m is mass of the electron, ω is the frequency of laser, ω_0 is oscillating frequency of the atom, D, G and F are second, third and fifth order anharmonic terms.

$$n^2 = 1 + \chi$$

$$\mathrm{Im}[\chi^5(\bar{\omega})] = \frac{Ne^6D^4[el(ad+bc)+f(ac-bd)]}{4m^5\varepsilon_0 A1.A2.(A3)^2.A4}$$

$$-\frac{GNe^6D^2(ad+bc)}{4m^5\varepsilon_0 A1.A2.(A3)^2.A4}$$

$$\frac{3GNe^6(ah+gb)}{16m^5\varepsilon_0 A1.A2.A5}$$

$$\frac{3Ne^6GD^2m(al+kb)+f(ak-bl)}{4m^5\varepsilon_0 A1.A2.A3.A4}$$

$$\frac{3Ne^6G^2(al+kb)}{16m^5\varepsilon_0 A1.A2.A4}$$

$$\left.\frac{FNe^6b}{16m^5\varepsilon_0 A1.A2}\right]$$

where

$$a = (\omega_0^2 - 25\omega^2)\,[(\omega_0^2 - \omega^2)^5 - 10\omega^2\Gamma^2(\omega_0^2 - \omega^2)^3 + 9\omega^3\Gamma^3(\omega_0^2 - \omega^2)^2 + 5\omega^4\Gamma^4(\omega_0^2-\omega^2)] + 5\omega\Gamma\,[\omega^3\Gamma^3(\omega_0^2 - \omega^2)^2 - 3\omega\Gamma(\omega_0^2 - \omega^2)^4 - \omega^5\Gamma^5 - 2\omega\Gamma(\omega_0^2-\omega^2)^4],$$

$$b = (\omega_0^2 - 25\omega^2)\,[\omega^3\Gamma^3(\omega_0^2 - \omega^2)^2 - 3\omega\Gamma(\omega_0^2 - \omega^2)^4 - \omega^5\Gamma^5 - 2\omega\Gamma(\omega_0^2 - \omega^2)^4] - 5\omega\Gamma\,[(\omega_0^2 - \omega^2)^5 - 10\omega^2\Gamma^2(\omega_0^2 - \omega^2)^3 + 9\omega^3\Gamma^3(\omega_0^2 - \omega^2)^2 + 5\omega^4\Gamma^4(\omega_0^2 - \omega^2)],$$

$$c = (\omega_0^2 - 4\omega^2)(\omega_0^2 - 9\omega^2) - 6\omega^2\Gamma^2,$$

$$d = -3\omega\Gamma(\omega_0^2 - 4\omega^2) - 2\omega\Gamma(\omega_0^2 - 9\omega^2),$$

$$e_1 = (\omega_0^2 - 4\omega^2),$$

$$f = -2\omega\Gamma,$$

$$g = (\omega_0^2 - 4\omega^2)^2 - 4\omega^2\Gamma^2,$$

$$h = -4\,\omega\Gamma(\omega_0^2 - 4\omega^2),$$

$$k = (\omega_0^2 - 9\omega^2),$$

$$l = -3\omega\Gamma,$$

$$m = (\omega_0^2 - 4\omega^2),$$

$$A_1 = [(\omega_0^2 - \omega^2)^2 + \omega^2\Gamma^2]^5,$$

$$A_2 = (\omega_0^2 - 25\omega^2)^2 + 25\omega^2\Gamma^2,$$

$$A_3 = (\omega_0^2 - 4\omega^2)^2 + 4\omega^2\Gamma^2,$$

$$A_4 = (\omega_0^2 - 9\omega^2)^2 + 9\omega^2\Gamma^2,$$

$$A_5 = [(\omega_0^2 - \omega^2)^2 + \omega^2\Gamma^2]^2.$$

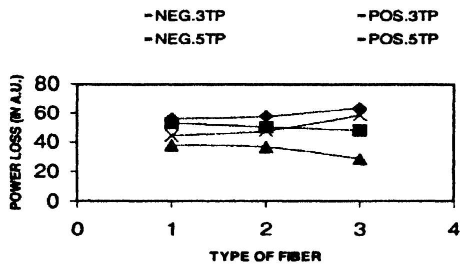

Figure 1. Power loss due to 3rd and 5th order nonlinearity *versus* type of fiber.

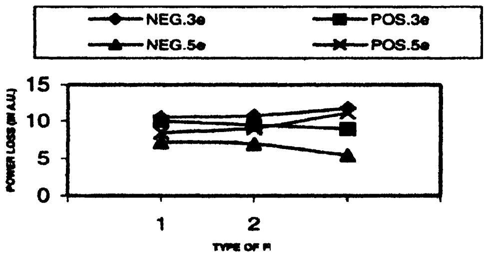

Figure 2. Electrostrictive power loss due to 3rd and 5th order nonlinearity *versus* type of fiber.

3. Results

Table 1. Power loss while considering second order nonlinearity.

Type of fiber	Nonlinear refractive index (in A.U.)	Power loss (in A.U.)	Damping factor (γ) (in A.U.)		$\mathrm{Im}[n_2^{(5)}(\omega)]$ (in A.U.)	Power loss due to γ (in A.U.)
Pure silica core fiber (1)	2.79	73.31	$\gamma_{1,2} = \pm 1\%$	$\gamma_1 = (-1\%)\gamma$	1.45	38.10
				$\gamma_2 = (+1\%)\gamma$	1.68	44.15
Dispersion shifted fiber (2)	3.35	88.03	$\gamma_{1,2} = \pm 2\%$	$\gamma_1 = (-2\%)\gamma$	1.4	36.79
				$\gamma_2 = (+2\%)\gamma$	1.8	47.30
Dispersion compensating fiber (3)	4.44	116.67	$\gamma_{1,2} = \pm 5\%$	$\gamma_1 = (-5\%)\gamma$	1.1	28.90
				$\gamma_2 = (+5\%)\gamma$	2.23	58.60

Table 2. Power loss due to Kerr and Electrostrictive effects while considering third order nonlinearity.

Type of fiber	Damping factor (γ) (in A.U.)	Nonlinear refractive Index (in A.U.)		Power loss (in A.U.)	
Pure silica core fiber (1)	$\gamma_1 = (-1\%)\gamma$	$n_{2k}^{(3)}$	1.74	$P_{2k}^{(3)}$	45.72
		$n_{2e}^{(3)}$	0.40	$P_{2e}^{(3)}$	10.51
	$\gamma_2 = (+1\%)\gamma$	$n_{2k}^{(3)}$	1.62	$P_{2k}^{(3)}$	42.57
		$n_{2e}^{(3)}$	0.38	$P_{2e}^{(3)}$	9.98
Dispersion shifted fiber (2)	$\gamma_1 = (-2\%)\gamma$	$n_{2k}^{(3)}$	1.78	$P_{2k}^{(3)}$	46.77
		$n_{2e}^{(3)}$	0.41	$P_{2e}^{(3)}$	10.77
	$\gamma_2 = (+2\%)\gamma$	$n_{2k}^{(3)}$	1.54	$P_{2k}^{(3)}$	40.47
		$n_{2e}^{(3)}$	0.36	$P_{2e}^{(3)}$	9.46
Dispersion compensating fiber	$\gamma_1 = (-5\%)\gamma$	$n_{2k}^{(3)}$	1.97	$P_{2k}^{(3)}$	51.77
		$n_{2e}^{(3)}$	0.45	$P_{2e}^{(3)}$	11.82
	$\gamma_2 = (+5\%)\gamma$	$n_{2k}^{(3)}$	1.47	$P_{2k}^{(3)}$	38.63
		$n_{2e}^{(3)}$	0.34	$P_{2e}^{(3)}$	8.93

Table 3. Comparison of Kerr and Electrostrictive power loss due to 2nd and 5th order nonlinearity.

Type of fiber	Nonlinear refractive index (in A.U.)		Power loss (2nd order) (in A.U.)		Im $[n_2^{(5)}(\omega)]$ (in A.U.)			Power loss (5th order) (in A.U.)	
Pure Silica						$N_{2k}^{(5)}$	1.175	$P_{2k}^{(5)}$	30.87
Core fiber (1)	n_{2k}	2.26	P_2	59.39	$\gamma_1 = (-1\%)\gamma$	$N_{2e}^{(5)}$	0.275	$P_{2e}^{(5)}$	7.22
						$N_{2k}^{(5)}$	1.361	$P_{2k}^{(5)}$	35.76
	n_{2e}	0.53	P_2	13.92	$\gamma_2 = (+1\%)\gamma$	$N_{2e}^{(5)}$	0.319	$P_{2e}^{(5)}$	8.38
Dispersion						$N_{2k}^{(5)}$	1.134	$P_{2k}^{(5)}$	29.80
Shifted fiber (2)	n_{2k}	2.72	P_2	71.48	$\gamma_1 = (-2\%)\gamma$	$N_{2e}^{(5)}$	0.266	$P_{2e}^{(5)}$	6.99
						$N_{2k}^{(5)}$	1.458	$P_{2k}^{(5)}$	38.31
	n_{2e}	0.63	P_2	16.55	$\gamma_2 = (+2\%)\gamma$	$N_{2e}^{(5)}$	0.342	$P_{2e}^{(5)}$	8.98
Dispersion						$N_{2k}^{(5)}$	0.891	$P_{2k}^{(5)}$	23.41
Compensating fiber (3)	n_{2k}	3.60	P_2	94.60	$\gamma_1 = (-5\%)\gamma$	$N_{2e}^{(5)}$	0.209	$P_{2e}^{(5)}$	5.49
						$N_{2k}^{(5)}$	1.807	$P_{2k}^{(5)}$	47.48
	n_{2e}	0.84	P_2	s22.07	$\gamma_2 = (+5\%)\gamma$	$N_{2e}^{(5)}$	0.423	$P_{2e}^{(5)}$	11.11

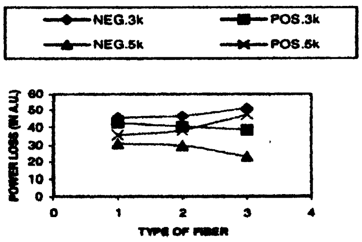

Figure 3. Power loss (Kerr) due to 3rd and 5th order nonlinearity *versus* type of fiber.

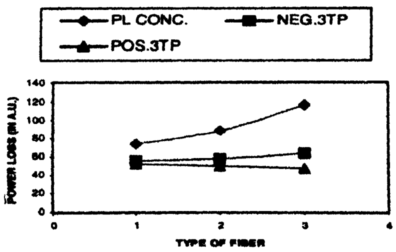

Figure 4. Power loss due to 2nd and 3rd order nonlinearity *versus* type of fiber.

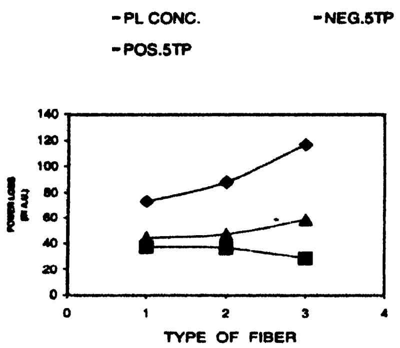

Figure 5. Power loss due to 2nd and 5th order nonlinearity *versus* Type of fiber.

4. Conclusions

The power loss due to Dispersion Compensating Fiber (DCF) is more than in Dispersion Shifted Fibers (DSF) which in turn has more loss in power than Pure Silica Core Fiber (PSCF). It shows that the power loss depends on refractive index of the optical material. With the increase in refractive index the coupling power also increases. Figure 1 shows that Kerr and Electrostrictive contribution to power loss due to 5th order nonlinearity is less than in case of 3rd order nonlinearity. Comparison of Figures 2 and 3 shows that the power loss due to Kerr effect is more than that due to Electrostrictive effects in higher order nonlinearity *i.e.* 3rd and 5th orders both. Kerr nonlinearity can be enhanced with increasing the coupling power [5]. We have calculated that the power loss due to Kerr effect increases with increase in refractive index (Figure 3) and hence with coupling power which is in confirmation with [4]. The contribution of power loss due to imaginary part of refractive index is significant and hence absorption, scattering and dispersion phenomena also play an important role in power loss in materials of optical fibers. A closer look at Figures 4 and 5 reveals the fact that with increase in order of nonlinearity, the power loss decreases. The loss tangent shows that the power loss due to 5th order is 10% of due to 3rd order. So the power loss due to the 7th order nonlinearity will be less than 5th order and hence the contribution of higher order nonlinearities is neglected.

Abrevations :

A.U. Arbitrary unit.

PL CONC. : Power loss while considering 2nd order nonlinearity and the effect of concentration of impurities on it.

NEG.3TP and NEG.5TP : Total power loss due to 3rd and 5th order nonlinearity using $\gamma_1 = (-x\%)\gamma$ (where $x = 1,2,5$).

POS.3TP and POS.5TP : Total power loss due to 3rd and 5th order nonlinearity using

$\gamma_2 = (+x\%)\gamma$

(where $x = 1,2,5$).

POS.3k and NEG.5k : Power loss due to 3rd and 5th order nonlinearity due to Kerr effect using

$\gamma_2 = (+x\%)\gamma$ and $\gamma_1 = (-x\%)\gamma$ respectively (where $x = 1,2,5$).

POS.3e and NEG.3e : Power loss due to 3rd and 5th order nonlinearity due to electrostriction using

$\gamma_2 = (+x\%)\gamma$ and $\gamma_1 = (-x\%)\gamma$ respectively (where $x = 1,2,5$).

References

[1] G P Agarwal *Nonlinear Fiber Optics* (San Diego, Calif · Academic) Ch 1, Sec 3, p16 (1989)

[2] Jan Jasny, Bernhard Nickel and Pawel Borowicz *J. Opt. Soc. Am.* **B21** 729 (2004)

[3] Eric L Buckland and W Boyd *Opt. Lett.* **22** 676 (1997)

[4] Sunita Sharma, S K Ghoshal and Devendra Mohan in *Microwaves and Optoelectronics* (eds) M D Shirsat *et al* (New Delhi : Anamaya Publishers) p411 (2004)

[5] Hai Wang David Goorskey and Min Xiao *Opt. Lett.* **27** 258 (2002)