Optik 125 (2014) 3679–3684

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Effect of sinusoidal ripples in refractive index profile distribution on the performance characteristics of dual concentric core step index fiber Raman amplifier

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ARTICLE INFO

Article history:
Received 16 July 2013
Accepted 9 January 2014

Keywords:
Profile structure with sinusoidal ripple
Raman fiber amplifier
Coefficient of dispersion
Effective area
Effective Raman gain coefficient

ABSTRACT

Phased matched wavelength, effective area, effective Raman gain, and wave guide dispersion are computed from exact numerical solution assuming scalar wave equation in the presence and absence of ripples as imperfections in the refractive index profile in dual cores of single mode fiber Raman amplifier for the first time. It is observed that for larger values of amplitude and lower frequencies, the effective Raman gain increases w.r.t. that calculated with no ripples. However, we assume ripple amplitude up to 5% of core cladding refractive index difference w.r.t. the available data, corresponding to the three ranges of relative ripple amplitudes of 1%, 2%, 3% and ripple frequencies of 1, 2, 3 μm^{-1}. Based on these data, we analyse performance of FRA over frequency shift band of 20–700 cm^{-1}. Uniformity of gain is interestingly seen to be maintained for higher ripple frequency and lower amplitude. However, no prominent effect in coefficient of dispersion and phase matched wavelength is observed within operating range of wavelength. Also, based on available structural parameter, the investigation should find use as a guide to system users to know the limit and promise of existence of ripples.

1. Introduction

It is well known that single mode fiber Raman amplifier (FRA), constructed by dual concentric cores meets up the high speed need of Internet traffic in WDM and DWDM because attenuated signals are optically amplified by the fiber based amplifier [1–5]. Here amplification of signals does not require any doping in narrow region of fiber core as is done in Erbium doped fiber amplifiers (EDFA). In case of FRA, stimulated Raman scattering (SRS), a non-linear optical phenomenon, is applied and the photon energy is utilised from one optical domain of higher frequency, known as a pump, to another domain at lower frequencies, known as the signal, for amplification [6–8]. Also the gain spectrum of FRA depends solely on the pump wavelength; hence it becomes simpler and easier to access S-band, inaccessible by EDFA's [9–13]. Thus FRA which can provide 3-dB bandwidth of 90–100 nm, has emerged as the potential solution to be used as an optical amplifier. Such uniform gain on the said band is not available either in EDFA or in semiconductor optical amplifier. Since the effective Raman gain coefficient [5], which is the ratio of Raman gain coefficient and effective area, assumes almost a uniform value with frequency shift in the said wavelength band, there is no restriction of selecting signal frequency band in FRA in which only we have to choose proper pump wavelength. We concentrate signals of wavelength to be amplified around a particular value in S-band.

Very recently, comparative studies of performance criteria of FRA with various refractive index profile distributions in core including step, parabolic, triangular [6,7] ones have received keen attention in relation to the variation of the effective Raman gain, effective area and dispersion coefficient with frequency shift keeping the phase matching condition fixed. Similar work has also included trapezoidal index profiles of practical interest [14]. Also investigation on FRA involving photonic crystal structures has started attracting interest in the context of signal amplification and dispersion compensation [15]. We have also studied how change in structural parameters like core gap radius [8] affects the effective gain, phase matched wavelength (PMW), dispersion characteristics, etc.

When we study in our simulation, we, ideally, assume that the optical fiber with step profile will be perfectly step but in actual practice, it is not so [16,17]; some deviations or changes as imperfections in the refractive index profile occur during fabrication across core radius and one should consider the existence of

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http://dx.doi.org/10.1016/j.ijleo.2013.10.127
0030-4026/

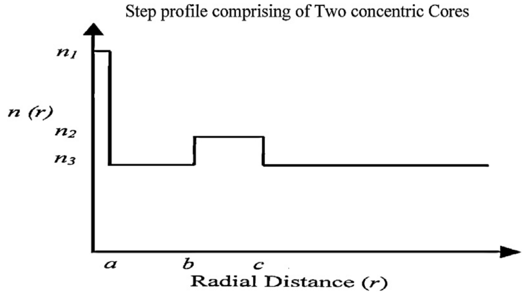

Fig. 1. Refractive index profile for step. x-axis: normalised radial distance (r/a); y-axis: refractive index ($n(r)$).

imperfections in practical profile while analysing the ideal profile theoretically. Examples of these defects are the radial appearance of dip or sinusoidal ripples over the step profile. There is a great deal of interest in studying the effect of ripples in the refractive index profile of graded index and step-index profile on dispersion, etc. [17]. However, it is seen that that such presence has nominal effect on propagation characteristics. But no such study is available in the context of ripples related to the performance characteristics of FRA.

Here, our aim is to investigate how the existence of ripples over step profile across the radius affects the performance characteristics of FRA keeping other structural parameters as obtained from [8] unchanged. For practical parameters to quantify ripples in relation to ripple free conditions, we follow the Ref. [17]. In subsequent sections, we present our theoretical analysis for computation and simulation together with result and discussions.

2. Theory

2.1. Profile structure and effective index

Our proposed optical fiber, shown in Fig. 1, has a coaxial refractive index profile with inner and outer cores with the presence of ripples. We confine our attention to a single mode regime with profile distribution as [6,7] as follows:

$$n^2(r) = \begin{cases} n_1^2[1-\Delta_1 f(\rho)] & \text{for} \quad 0 \le \rho \le 1 \\ n_3^2 & \text{for} \quad 1 \le \rho \le b \\ n_2^2[1-\Delta_2 f(\rho)] & \text{for} \quad b \le \rho \le c \\ n_3^2 & \text{for} \quad c \le \rho \end{cases} \tag{1}$$

where n_1, n_2 and n_3 are respective refractive indices of the first core, second core and cladding of step index fiber; $\Delta_1 = (n_1^2 - n_3^2)/n_1^2$, $\Delta_2 = (n_2^2 - n_3^2)/n_2^2$; Δ_1 and Δ_2 are the respective grading parameter, $\rho = r/a$; r is the radial distance and a is first core radius; b is the core gap radius; $(c-b)$ is second core width. The profile function, $f(\rho)$ is given as $f(\rho) = \rho^q - g\sin 2\pi\,\nu\,\rho$; here q, being the profile exponent, gives the profile shape and tends to ∞ for step profile. g and ν are respectively amplitude and spatial frequency w.r.t. radial distance. For $g = 0$ and $\nu = 0$ equation (1) reduces to ideal step profile considered in previous work [5–14].

The entire refractive index profile is sampled into small units of rectangle to compute the field distribution in each rectangular segment and effective index of refraction (n_{eff}). The total field is the vector sum of all such segment based fields [18]. The effective refractive index bears the relation with propagation constant and wave number,

$$\beta^2 = k_0^2 n_{eff}^2 \tag{2}$$

where $\beta = 2^{\pi/\lambda}$ is the propagation constant in the dielectric media of optical fiber with $k_0 = 2\pi/\lambda_0$ being the free space wave vector, whereas λ and λ_0 being the wavelengths in the medium and free space, respectively. Thus one may take n_{eff} as a ratio of λ_0/λ.

2.2. Scalar wave equation

In order to find pump and signal fields and effective refractive indices, we use the following scalar wave equation under weakly guiding approximation [19]:

$$\frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + [\omega^2\varepsilon(r)\mu_0 - \beta^2]\psi(r) = 0 \tag{3}$$

where $\varepsilon(r)$ is dielectric permittivity of optical fiber at radial distance r, μ_0 is free space permeability of the medium. The modal field is expressed by Bessel and modified Bessel equation as

$$\psi(r) = \begin{cases} AJ_0(\kappa r) + BY_0(\kappa r) & \text{for} \quad n(r) > n_{eff} \quad (4) \\ CI_0(\omega r) + DK_0(\omega r) & \text{for} \quad n(r) < n_{eff} \quad (5) \end{cases}$$

with κ^2 and ω^2 are given as

$$\kappa^2 = k_0^2[n^2(r) - n_{eff}^2] \tag{6}$$

$$\omega^2 = k_0^2[n_{neff}^2 - n^2(r)] \tag{7}$$

The effective refractive index (n_{eff}), constants A, B, C and D and the field, $\psi(r)$ in the above equations are evaluated by matrix method [18] where we partition the whole index profile of the proposed optical fiber into smaller rectangular segments and by apply boundary condition of continuity with the field $\psi(r_i)$ and $(\partial\psi(r_i))/\partial r$ for ith and $(i+1)$th segments. In the next section, we present the results and discussions based on our simulation work using MATLAB 7.0 and involving the above theoretical framework [18].

2.3. Raman gain model

For small signal regime, one can ignore the pump depletion due to SRS. The variations of pump power (P_p) with pump wavelength λ_p and signal power (P_s) with signal wavelength λ_s are described by the following couple mode equation [3,5]:

$$\left.\begin{aligned} \frac{dP_p}{dz} &= -\alpha_p P_P, \\ \frac{dP_s}{dz} &= \gamma_R P_P P_S - \alpha_s P_s \end{aligned}\right\} \tag{8}$$

where α_p and α_s are attenuation coefficients at pump and signal wavelength λ_p and λ_s respectively, γ_R being effective Raman gain coefficient, given as [2,6]

$$\gamma_R = \frac{g_R(\upsilon)}{A_{eff}} \tag{9}$$

where $g_R(\upsilon)$ is Raman gain coefficient at particular frequency shift; the frequency shift in this process where a high pump power is needed for Raman amplifier, is determined as [15]

$$\Delta\nu = [\nu_p - \nu_s] = \frac{1}{\lambda_p} - \frac{1}{\lambda_s} \quad (m)^{-1} \tag{10}$$

with A_{eff} as the effective area, defined in terms of pump and signal modal fields as

$$A_{eff} = 2\pi\frac{\int \psi_p^2 rdr \int \psi_s^2 rdr}{\int \psi_p^2\psi_s^2 rdr} \tag{11}$$

and is computed from the overlap integral of two modal fields [5–14]. In the FRA structure, the effective area, A_{eff} varies in such