Fiber Design for Broad-Band Gain-Flattened
Raman Fiber Amplifier

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ABSTRACT—We report here a novel fiber design which has inherently flattened effective Raman gain spectrum, with a relative 3-dB bandwidth of ~90 nm. Gain-flattened broad-band amplification can be achieved in any wavelength band by suitably choosing the fiber parameters and the pump wavelengths. Simulations show that the proposed fiber also has high negative dispersion coefficient (~(-300 to -600) ps/km • nm in the operating range of wavelength. Hence, the designed fiber serves the purpose of a gain-flattened broad-band amplifier and dispersion compensator.

Index Terms—Modeling, optical amplifiers, optical fiber amplifiers, Raman scattering.

I. INTRODUCTION

WITH THE growth of Internet traffic, there has been a growing interest in increasing the number of wavelength channels and their data-carrying capacity in the current wavelength-division-multiplexed (WDM) systems. However, the capacity of current WDM systems is limited by the narrow bandwidth of erbium-doped fiber amplifiers. To overcome this limitation, recently there has been a lot of interest in Raman amplifiers, which have been shown to provide bandwidths up to 10-12 THz. Another important feature of Raman amplifiers is that the gain band is determined by the pump wavelength only.

Although the effective Raman gain (Raman gain coefficient/effective area) spectrum in conventional single-mode fibers has a gain bandwidth of over 40 THz, the spectrum is flat only over a narrow range of wavelengths. In practice, for broad-band applications, gain flattening is achieved by using properly chosen multiple pump wavelengths with specific power levels. Several design algorithms have been proposed to achieve a flat gain spectrum using a large number (~ 10-12) of pumps [1], [2]. This technique requires tedious design procedures for finding out the proper wavelengths and power levels of various pumps in order to obtain a flat spectrum. Also, this is an expensive technique to implement. In this letter, we present a novel fiber design, in which it is shown through simulations that the effective Raman gain spectrum is inherently flat over a relative 3-dB bandwidth as large as ~90 nm. The fiber has been designed in a manner that, in the wavelength range where Raman gain coefficient (gn) decreases, the effective area of interaction (Aeff) also decreases in almost the same manner, such that the effective gain (gR/Aeff) is reasonably flat over a large wavelength range. An added advantage of this design is that it has a large negative dispersion coefficient (~(-300 to -600) ps/km • nm in the operating range of wavelength. Hence, the proposed fiber is expected to serve the purpose of broad-band amplification along with dispersion compensation.

II. MODELING OF RAMAN GAIN

In the small signal regime, pump depletion due to Raman scattering can be neglected and the evolution of pump and signal powers can be described by following equations [3]:

\[ \frac{dP_p}{dz} = -a_p P_s \]
\[ \frac{dP_s}{dz} = a_s P_p - \alpha_s P_s \]

where z is distance, \( P_p \) and \( P_s \) are pump and signal power levels, respectively, \( a_p \) and \( a_s \) are the attenuation coefficients at pump and signal wavelengths, respectively, and \( 1R = \text{effective Raman gain, defined by [4]} \]

\[ 1R = \frac{\int g_i(v, r) \psi^2_p \psi^2_s dA d\lambda}{2\pi \int \psi^2_p dA d\lambda} \]

where \( g_i(v, r) \) is the spontaneous Raman gain coefficient at a frequency shift v from the pump frequency and at a position specified by a cylindrical coordinate r and \( ip \), and \( i\psi \) are the modal fields at pump and signal wavelengths, respectively. It is usual practice to write (3) as

\[ 1R = \frac{gR(v)}{A_{eff}} \]

with

\[ A_{eff} = \frac{\int \psi^2_p \psi^2_s |r| dA d\lambda}{\int \psi^2_p dA d\lambda} \]

being the effective area and \( gR(v) \) is the Raman gain coefficient corresponding to the core of the fiber. In our analysis, all calculations have been carried out using (3).

For a conventional fiber design, the variation of \( iij_i(r) \) over the signal band is usually small and, hence, the effective Raman gain spectrum defined by \( 1R \) closely follows the curve of \( gR(v) \).

The spectral dependence of \( gR(v) \) could be very different if \( iij_i(r) \) has a strong wavelength dependence over the signal bandwidth. Since \( \psi(v) \) decreases rapidly from its peak value at \( v \approx 13.2 \) THz, with decrease in v, a flattening of the effective Raman gain \( 1R \) can be achieved if the effective area
III. FIBER DESIGN

Fig. 1 shows the refractive index profile of the proposed fiber, which has a dual core design that was originally proposed [5] to achieve flat dispersion for broad-band dispersion compensation. It consists of two concentric cores, the inner core with large $A$ and outer core with small $A$. Here, $A$ is defined as $A_i = (nf - n)/2nI$. The parameters of the two cores are so chosen that each of these supports a single azimuthally symmetric mode in the operating range of wavelength. The parameters for the proposed design are $n_i = 1.47299$, $n_2 = 1.44871$, and $n_3 = 1.444388$ (corresponding to pure silica) at 1550 nm, $a = 1.6 = 9$, and $c = 16.32 \, \mu\text{m}$. These parameters are so optimized such that the two individual modes (corresponding to the inner and outer core) are nearly phase matched at ~1520 nm (Fig. 2). Hence, the modal fields at the pump wavelength (chosen to be 1465 nm) and the signal wavelengths below 1520 nm will be tightly confined to the inner core and, thus, the pump and signal overlap will be high, giving a small $A_{s\delta}$. However, as the signal wavelength approaches and crosses the phase matching wavelength, the fractional power of the fundamental mode will gradually increase in the outer core. Hence, the overlap between the pump and the signal fields starts to decrease, increasing the effective area. Thus, by suitably choosing the fiber parameters, phase matching wavelength and the pump wavelength, one can ensure that the decrease in $A_{s\delta}$ almost compensates for the decrease in the Raman gain coefficient, such that a flat effective gain spectrum is achieved.

IV. NUMERICAL RESULTS AND DISCUSSION

Raman gain coefficient for a certain germania concentration ($\#\text{GeO}_2$) can be calculated using [4]

$$g_R(x,\lambda) = \frac{n_2^2}{n_1^2} g_R(S, \nu)$$

$$+c(\nu) x_{\text{GeO}_2} g_R(S, \nu) \frac{\lambda_s^2}{\lambda_{\text{Peak}}^2}.$$  (6)

Here $n_1$ and $n_2$ are the refractive indexes of GeO$_2$ doped region and pure silica, respectively. $\lambda_{\text{Peak}}$ is the peak Raman gain coefficient of silica, $\nu_{\text{peak}}$ is the Stokes wavelength corresponding to peak gain. $C(y)$ is a linear regression factor; its spectral variation is given in [6]. The peak value of Raman gain coefficient for silica ($\nu = 13.2$ THz, for copolarized pump and signal, at a pump wavelength of 1465 nm is $1.0356 \times 10^{-13} \text{ m/W}$ [4]. All through the analysis, we have assumed the pump and signal beams to be copolarized. To calculate the modal fields and the effective refractive indexes for the proposed fiber, the solutions in each region are written in terms of Bessel functions and appropriate boundary conditions are applied to obtain an eigenvalue equation, which has been solved numerically.

Fig. 3 shows the spectral variation of $A_{s\delta}$ and $g_R(x,\lambda)$ (corresponding to the inner core) for the given fiber profile. As can be seen, the variations over the range 100-400 cm$^{-1}$ are very similar and, thus, should lead to an almost constant value of $JR$ over this spectral range. Fig. 4 shows the effective Raman gain
spectral design. One can note that high negative dispersion coefficient is achievable with this design, which makes it suitable for application in broad-band amplification with dispersion compensation [5]. Since the proposed fiber supports more than one mode, it is important to couple light only in the fundamental mode. This can be achieved by tapering the fiber at both the ends, so that at the splice joint with the conventional single-mode fiber, only the fundamental mode of the proposed fiber gets excited. Thus, an adiabatic taper would then provide a selective excitation of the fundamental mode of the designed fiber.

V. CONCLUSION

We have proposed a novel fiber design with broad-band flat effective Raman gain spectrum over a relative 3-dB bandwidth of ~90 nm. Simulations show that the fiber also has a high (300 to -600) ps/km • nm, negative dispersion coefficient over the operating range of wavelength. This makes the proposed fiber a suitable candidate for dispersion compensation along with broad-band Raman amplification. Gain-flattened broad-band amplification is achievable in any wavelength band by suitably choosing the fiber parameters and the pump wavelength.

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REFERENCES