Novel optical fiber designs for gain flattened optical amplification and dispersion compensation

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Abstract Optical amplifiers and dispersion compensators form important components of any DWDM system and the overall performance of the system depends critically on the spectral properties of these and other components in the link. This has led to the development of optical amplifiers and fiber based dispersion compensators with specific wavelength dependent characteristics. Dual concentric core fibers and asymmetric twin core fibers possess very interesting modal characteristics in terms of chromatic dispersion, spectral dependence of modal field profiles and bend induced attenuation etc. and with proper designs they can be tailored to have the desired spectral properties. This talk will present our recent work on different novel dual concentric core and asymmetric twin core fiber designs for efficient dispersion compensation and achieving intrinsically flat gain EDFAs in C-band and S-band and flat gain Raman fiber amplifiers.

Key words: Dispersion compensating fibers, Raman fiber amplifier, Gain flattening

INTRODUCTION

The increase in Internet traffic has led to an augmented demand for higher transmission capacity and dense wavelength division multiplexing (DWDM) technology has emerged as the most favorable solution to this growing demand. Due to inherent characteristics of the optical fiber, the signal carrying optical pulses need to be periodically compensated for dispersion as well as attenuation. In this regard dispersion compensating fibers and optical amplifiers have emerged as very attractive solutions since they provide for the compensation in the optical domain itself without converting the signals into the electrical domain.

The capacity of current WDM systems is, however, limited by the narrow bandwidth of Erbium doped fiber amplifiers (EDFAs) and gain flattened Raman fiber amplifiers (RFA), which have been shown to provide bandwidths upto 10 to 12 THz, have emerged as the potential solution to this limitation. Another important feature of Raman amplifiers is that the gain band is determined by the pump wavelength only, which makes it much simpler to achieve amplification in otherwise inaccessible bands. 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 broadband 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.

In this paper we discuss some novel fiber designs for achieving simultaneously flat Raman gain using a single pump as well as compensation of accumulated dispersion. We also discuss novel EDFA designs working in the S-band.

Flat gain Raman fiber amplifier

Figure 1 shows the refractive index profile of a dual concentric core fiber design for achieving flat gain Raman amplification. It consists of a central high $\Delta$ core with a concentric second core of smaller $\Delta$. The dual concentric core fiber is like a directional coupler with the two interacting waveguides being a fiber with the inner core only (rod fiber) and a fiber with the outer core only (tube fiber). If the two waveguides are chosen to be significantly non-identical, the dispersion curves of the individual modes of the inner and outer core will be
different. At some chosen design wavelength, referred to as the phase matching wavelength (PMW), they can be made to have the same propagation constant (phase matched) and in such a case, the normal modes of the coaxial fiber (which are a linear combination of the individual modes of the two cores) will undergo rapid changes in effective indices as well as modal field distributions while passing through the PMW. Figure 2 shows a typical variation of the effective indices of the fundamental and the first azimuthally symmetric modes showing the rapid variation of the effective indices of the normal modes around the PMW. For wavelengths much below the PMW, the effective index of the fundamental mode of the composite fiber is very close to that of the rod fiber and for wavelengths much larger than the PMW, the effective index of the fundamental mode would be very close to that of the tube fiber. Thus around PMW, the effective index variation with wavelength is far from linear and this is expected to lead to a very large value for the dispersion coefficient for this normal mode [3-4] leading to applications in dispersion compensating fibers.

The specific variation of the effective index of the fundamental normal mode also leads to a significant shift of the field distribution of the mode from being concentrated around the inner core (for wavelengths shorter than the PMW) to being concentrated in the outer core (for wavelengths longer than the PMW). This modal power redistribution can also be employed for achieving various features such as gain flattening in erbium doped fiber amplifiers or Raman fiber amplifiers [5-8]. Figure 3 shows the net Raman gain spectrum (with ± 0.2 dB gain ripple) that is achieved from the proposed design for a single input pump with a power of 520 mW and a fiber length of 12.5 km. Due to the rapid variation of effective index close to the PMW, the fiber also has a large negative dispersion coefficient of −580 to −515 ps/km-nm in the S-band and thus can compensate for accumulated dispersion in the link. Figure 4 shows the residual dispersion after 5 spans of G.652 fiber and 12.5 km of the designed fiber [8]. Thus the proposed fiber is a spectrally flat lossless dispersion compensating fiber capable of compensating dispersion over a number of spans of the link.
In the dual concentric core design, the two interacting cores are concentric. The same principle of achieving special modal characteristics as in the dual concentric core fiber can be achieved by using an asymmetric twin core (ATC) fiber design shown in Fig. 5. Unlike the dual concentric core fiber, an ATC fiber consists of two parallel, non-identical cores; these find applications as wavelength filters, couplers etc [9, 10]. The two cores, each supporting a single mode, can be designed to have the same propagation constant at a chosen wavelength - the phase matching wavelength (PMW). In terms of supermodes, this structure supports one even and one odd supermode, having typical spectral variation of effective indices similar to that shown in Fig. 2 for a dual concentric core. Just like for the dual concentric core design, far away from the PMW, the effective indices of the two normal modes are very close to those of the individual modes and as the wavelength sweeps across the phase matching wavelength, the effective index varies in a highly nonlinear fashion leading to very large negative dispersion coefficient, so that the fiber can act as a dispersion compensating fiber. The modal field also redistributes itself between the two cores as the wavelength changes around the PMW.

In view of the special design of this fiber, the variation in the Raman gain coefficient of the fiber can be compensated by a wavelength dependence of the modal effective area. Thus such a fiber can also act as a broadband, lossless dispersion-compensating module (DCM) [11]. Figure 6 shows the net gain spectrum (± 0.1 dB gain ripple) corresponding to 12.5 km long ATC Raman fiber amplifier which is pumped by 315 mW of pump power and with 32 channel input with 0.1 mW each channel. Thus such a fiber can act as a lossless dispersion compensating module for the S-band. Since the amplification is based on Raman scattering, the design can easily be extended to other bands such as C-band or L-band.

**S-band EDFA**

S-band amplifiers based on silica based erbium doped fibers have also been recently reported. It has been shown that efficient S-band EDFA require high inversion levels along the fiber and C-band ASE suppression, which otherwise depletes the population inversion. It is possible to achieve an efficient single stage S-band EDFA based on a co-axial core fiber (see Fig. 1) wherein distributed ASE filtering is achieved by winding the fiber with an optimally chosen bend radius. Bend loss usually has a strong spectral variation because of the variation of mode field diameter (MFD) with wavelength. Co-axial fiber design provides extra degrees of freedom in terms of tuning the bend loss variation. Hence, by optimising the fiber parameters and the bend radius, we have ensured that wavelengths above 1525 nm suffer a high (> 6 dB/m) bend loss, whereas the wavelengths below 1525 nm suffer minimal loss. In our proposed fiber, bend loss at 1530 nm is 100 times greater than that at 1490 nm, which leads to a high net gain in the S-band. [12]. Figure 7 shows the normalized forward ASE power spectral density of 7.5 m of the designed fiber pumped by 500 mW of 980 nm pump without a bend (solid curve) and with a bend (dotted curve) of 3 cm radius. It is clear that the bend induced loss shifts the ASE spectrum into the S-band. Figure 8 shows a typical gain and noise figure spectrum of an S-band EDFA based on the proposed fiber design. As compared to an earlier reported design, based on W-index fiber, the proposed design has a very compact configuration because of single stage amplification and spooling with 3 cm bend diameter. In addition, using this design, we have been able to achieve inherent gain flattened S-band amplification operation with ± 2.9 dB gain ripple over 30 nm wavelength range. Such designs can lead to compact EDFAs working in the S-band and in conjunction with EDFAs operating in the C-band and L-band, these can offer us EDFAs covering a much larger spectral band.
Conclusions

Coaxial core designs and asymmetric twin core designs provide us with additional degrees of freedom to tune the modal properties of the propagating mode. This can be used to achieve large dispersion coefficient for dispersion compensation applications as well as achieving inherent Raman gain flattening using a single pump or for achieving efficient S-band EDFAs.

References