Distinctive Behaviour of Long-Period Gratings in Amplifying Waveguides

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Abstract: We describe a tuneable filter based on a long-period grating written in Er^{+3}-doped core fiber. Integration of filtering and amplifying properties results in qualitatively new operational behaviour, that otherwise is impossible to realize using conventional gratings.

OCIS codes: (060.2410) Fibers, erbium; (060.2340) Fiber optics components; (230.1950) Diffraction gratings

1. Introduction

Growing demand for the deployment of high bandwidth services closer to the end customer means a new class of amplifiers for regional, metro-core, and metro-access networks will be needed [1]. They require complex loss/gain elements to compensate for changes in amplifier operating conditions. Long-period gratings (LPGs) are traditionally used as gain equalizers in broadband Er-doped amplifiers. In this paper we analyze an LPG directly written in a amplifying fiber, as a complex loss/gain element.

2. Cladding mode losses versa core mode gain

Using an example of mode interaction in a LPG we have shown [2, 3] that cladding mode losses can play an important role in the process of grating assisted coupling light between the fiber core mode, where it is normally launched, and the cladding mode(s). Normally this light begins to return back into the core when the grating strength, κL is higher than $\pi/2$, where L is the grating length, and κ is the coupling coefficient. However, certain levels of cladding mode losses can attenuate the mode to the extent that no light is returned to the low-loss core mode. This regime of LPG operation prevents the mode interference and leads to a smooth, sidelobe-free transmission spectrum. The complex amplitude of the core mode, where the signal is initially launched, is described by a well-known equation:

$$T_{11} = \left[\cos(\gamma L) + j\frac{\sigma}{\gamma}\sin(\gamma L)\right]\exp(j(\beta_{10} - \sigma)L); \quad (1)$$

where $\sigma=(\beta_{10} - \beta_{20} - 2\pi/\Lambda)/2$ is the detuning factor, $\beta_{10} = \beta_1 + j\alpha_1$ is the propagation constant of the core mode, $\beta_{20}=\beta_2+j\alpha_2$ is the propagation constant of the interaction cladding mode with α_1 and α_2 accounting for loss/gain of the modes, Λ is the LPG period, and $\gamma=(\sigma^2+|\kappa|^2)^{1/2}$, where κ is the mode coupling coefficient. Imaginary parts of the propagation constants take their positive values in the case of losses, and they are negative if there is any gain in the core or/and cladding. At the wavelength where the mode matching condition is satisfied, the detuning factor becomes purely imaginary: $\sigma=-j(\alpha_2 - \alpha_1)/2$ with the core losses normally much lower than the cladding losses: $\alpha_2 >> \alpha_1$. Substituting this σ expression at the resonance wavelength into Eq.1, and equating it to zero, we get a relationship between the grating strength, κL, and the dimensionless loss factor, $q=(\alpha_2 - \alpha_1)/(2\kappa)$:

$$\cos\left(\sqrt{1-q^2}\,\kappa L\right)+\frac{q}{\sqrt{1-q^2}}\sin\left(\sqrt{1-q^2}\,\kappa L\right)=0 \qquad (2)$$

In Fig.1 the solution of Eq.2 is presented in dimensionless variables: κL and q. As we can see from the plot, there is no solution for $0<\kappa L<\pi/2$, i.e. it is impossible to achieve the full signal attenuation for this κL values (unless the cladding mode has a gain instead of loss). However, cladding mode losses allow us to provide 100% attenuation for any value of $\kappa L>\pi/2$. This cladding mode loss drastically changes the grating performance. Unlike the case of loss-free grating, where the 100% coupling from the core into the cladding mode is possible only for discreet values of $\kappa L = m\pi/2$, (m is an integer), the optimum loss value in the cladding provides 100% power removal from the core for any $\kappa L>\pi/2$ with essentially sidelobe-free transmission spectrum.

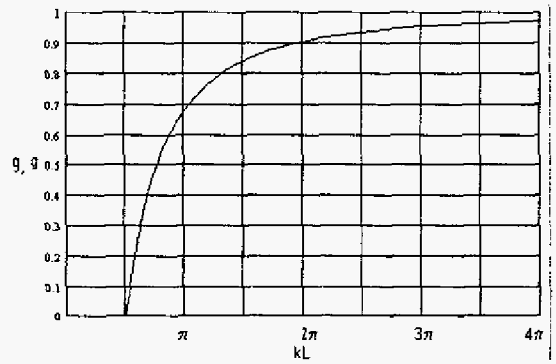

Fig.1. Optimum gain/loss factors vs. LPG strength.

This result helps us to realize that the same Eq.2 is valid for the situation when there is a gain in the core mode whereas the cladding mode can suffer certain losses. The loss factor in Eq.2 has to be replaced with a gain factor $g=(|\alpha_1|+\alpha_2)/(2\kappa)$, the rest remaining unchanged. Eq.2 and the plot in Fig.1 relates the grating strength with the core gain value that is required to completely attenuate the core mode at the resonance wavelength. As was the loss case, the solution to Eq.2 with respect to g exists only for $\kappa L>\pi/2$.

For the calculation we use the following LPG parameters: effective core and cladding mode indices are n_1=1.457 and n_2=1.450, respectively. To couple these modes at 1.555 μm wavelength, the LPG should be written with the period 220 μm.

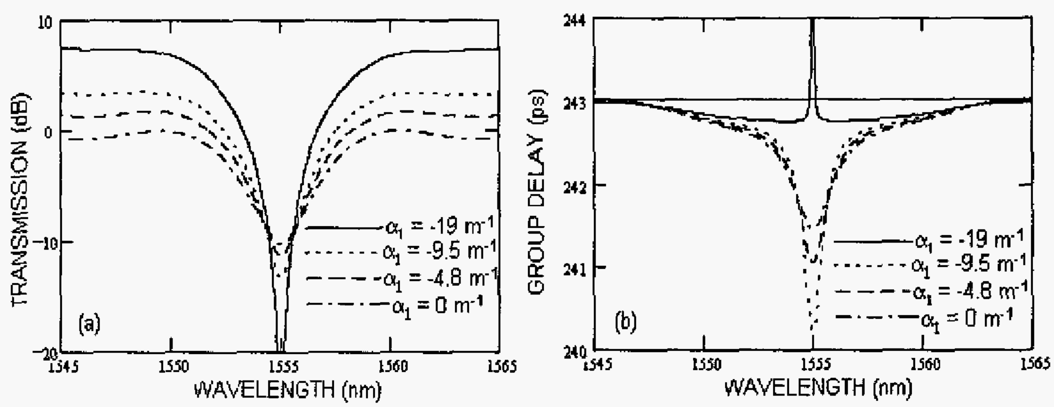

Fig.2.Core mode transmission and group delay.

The solid curve in Fig.2a represents a transmission spectrum in logarithmic scale for the optimum level of gain (α_1 = -19 m^{-1} or 1.652 dB/cm) for a 50 mm long grating with the strength of $\kappa L = 0.6\pi$ and the loss-free cladding mode (α_2 = 0). This optimum gain leads to essentially complete mode attenuation (more than -50 dB) at the resonance wavelength with close to 8 dB amplification at the wavelengths outside the resonance. It is interesting to note that, over the range of gain values ($0 < \alpha_1 \le (\alpha_1)_{opt}$), the higher the amplification outside the resonance, the higher the attenuation at the resonance itself. This is a type of negative feedback that can be used in different amplifying and lasing devices. If we continue to increase gain higher than $(\alpha_1)_{opt}$ the attenuation starts to decrease. For example, for $\alpha_1 = 1.5(\alpha_1)_{opt}$ the attenuation jumps to just -6.3 dB. Signal transmission in the cladding mode (Fig.3a) experiences amplification in the FWHM bandwidth of about 5 nm. It reaches 4.3 dB amplification for $\alpha_1 = (\alpha_1)_{opt}$ (solid curve). The sidelobes can be suppressed by the grating apodization.

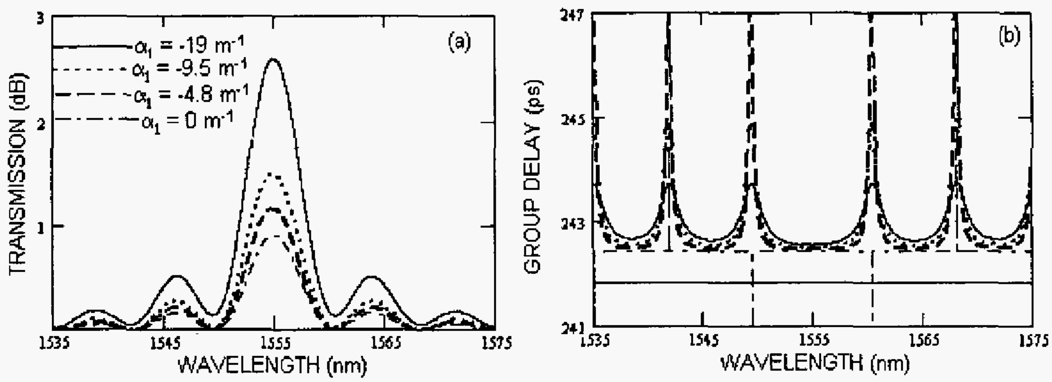

Fig.3.Cladding mode transmission and group delay.

It takes light n_1L/c =243.013 ps and n_2L/c =241.834 ps to travel through the unperturbed fiber of length L=5 cm in the core and in the cladding modes, respectively. These times are marked by a horizontal lines in Fig.2b and 3b. The grating introduces delay or speed-up the light propagation. It is not surprising that the time delay at the resonance wavelength is approaching infinity in Fig.2b for $\alpha_1 = (\alpha_1)_{opt}$. Indeed, there is no energy transmission at this wavelength. What is surprising is that it changes the tendency of increasing light speed-up in the vicinity of the resonance to decreasing when α_1 approaches $(\alpha_1)_{opt}$. The gain presence drastically changes the time delay in the cladding as well (Fig.3b). For loss/gain free LPG the cladding mode always travels slower, $(n_1+n_2)L/2c$, than in the unperturbed fiber, n_2L/c, with periodical sharp jumps at the wavelengths where there is no transmission. The gain presence in the core blurs these sharp peaks resulting in a quasi-periodic variation of the time delay over very broad spectral range. The above example also shows that gain control can be strong mechanism of the dispersion control.

3. Conclusions

Using example of LPG written in rare-earth doped core fiber, we have shown that integration of filtering and amplifying properties produces qualitatively new properties, that otherwise are impossible to realize when the filtering and amplification are functionally separated. The results obtained outline opportunities in designing new tuneable filters on the integrated optics platform. Combination of pump-driven gain control and electro-optic tenability in grating-assisted co-directional coupler instead of LPGs opens a promising approach to the next generation of photonic components.

4. References

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