1606

Submitted to Optics Letters

Accurate Tuning of Mismatched Twin-core Fibre Filters

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Abstract:

We have demonstrated a reproducible and accurate way of tuning the coupling wavelength of a mismatched twin-core filter. This allows high quality all-fibre filters to be implemented with low loss at any desired wavelength over a range of few hundred nanometres from the same fibre. A ~500 nm range tuning is demonstrated, limited only by the measurement set-up, not by the technique itself. The highly accurate control of the filtering wavelength in combination with filtering strength control by adjusting the length of the twin-core fibres, allows complex filter profiles to be implemented by cascading several of different filters. These filters are also very stable to a change in temperature (~0.26 nm/100°C at 1.55 μm) and strain (7.8×10^{-3} nm/mStrain at 1.55 μm), allowing easy packaging.

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There are many applications of optical fibre filters in optical fibre systems e.g. filtering of amplified spontaneous emission after an erbium-doped fibre amplifier (EDFA) and loss filters for gain equalisation in an EDFA. The current commercially available bandpass filters, e.g. devices based on thin film technology, fibre Fabry Perot and recently fibre gratings with circulators, are in one way or another based on some bulk optic techniques. Recently, due to a surge of interest in wavelength-division-multiplexing systems, spectral dependent loss with designed profiles becomes a very interesting topic for many who want to achieve a wide bandwidth EDFA. The dominant technology for achieving this so far has been long period photosensitive gratings written in fibres using a UV laser to couple a guided mode into a cladding mode [1]. This method allows accurate control of the bandstop filter response and can therefore implement complicated spectral loss profiles required. However, the response of these gratings is highly sensitive to a change of temperature and strain, decay of the photosensitive index change and out-diffusion of hydrogen, should low temperature hydrogenation be used. This makes it very difficult to predict the final device response during fabrication and other technologies have to be employed to maintain the same grating response at different operational conditions. To reduce the temperature sensitivity, specially designed fibres are normally used [2,3].

All-fibre filters based on mismatched twin-core (TC) fibres designed to phase-match at the filtering wavelength have been proposed and demonstrated sometime ago[4,5,6]. In this paper, we demonstrate a highly reproducible and accurate way of tuning the coupling wavelength of a mismatched TC fibre, allowing the coupling wavelength to be accurately positioned at any wavelength over a few hundred nanometre wavelength range. The diameter of the TC fibre is reduced on a coupler rig. The highly controllable reduction of TC fibre diameter is used to adjust the coupling wavelength of the TC fibre. A tuning range of ~500 nm has been demonstrated, only to be limited by our measurement set-up, not by the technique itself. Bandpass and bandstop filters of very high spectral quality have been implemented to demonstrate the potential of the technique. The accurate tuning technique, in combination with strength tuning by adjusting the length of the TC fibre, allows spectral dependent loss of various profiles to be realised by cascading the filters. Unlike long period gratings, the filter response is intrinsically very stable in terms of temperature and strain change, allowing easy packaging. It has a temperature sensitivity of ~0.26 nm/100°C and a strain sensitivity of $\sim 7.8 \times 10^{-3}$ nm/mStrain at 1.55 μm. Both of these specifications indicate improved environmental stability over a fibre Bragg grating (~1.0 nm/100°C and ~1.2 nm/mStrain at 1.55 μm).

In a mismatched TC fibre with cores with respective propagation constants β_1 and β_2 ($\beta_1 > \beta_2$), core radii ρ_1 and ρ_2, and relative index differences Δ_1 and Δ_2, the mismatching between the two cores is usually sufficient large to suppress any intrinsic coupling between the two cores when the phase-matching condition is not met. In such a fibre when not phase-matched, the fundamental normal modes of the TC fibre (odd and even modes), resemble very closely each of the core modes when the two cores are in isolation, and we can therefore use β_1 and β_2 as the propagation constants of the two modes while maintaining a good accuracy. This dramatically simplifies the analysis of such structures. The TC fibre can be designed to achieve phase-matching at a wavelength λ_0, where the two propagation constants are equal and $\beta_1(\lambda_0) = \beta_2(\lambda_0)$. The coupling only happens over a very small wavelength range (see fig.1). Please note that the propagation constants of real fundamental mode in the TC fibre (odd and even modes) at the coupling wavelength will deviate more from β_1 and β_2. For simplicity, we use the approximation of β_1 and β_2 throughout the wavelength range. Therefore at λ_0

$$\beta_1(\lambda_0) = \frac{1}{\rho_1}\sqrt{\frac{V_1^2}{2\Delta_1} - U_1^2} = \beta_0$$

$$\beta_2(\lambda_0)=\frac{1}{\rho_2}\sqrt{\frac{V_2^2}{2\Delta_2}-U_2^2}=\beta_0$$

V_1, V_2, U_1 and U_2 are as normally defined in a optical fibre respectively for the two cores at the coupling wavelength λ_0. It is clear that if the diameter of the fibre is reduced from a_0 to $a=Ra_0$, then the two core radii become, respectively, $\rho_1'=R\rho_1$ and $\rho_2'=R\rho_2$. The coupling wavelength will be changed to λ_0' with the new propagation constant at the coupling being $\beta_0'=\beta_0/R$. V_1, V_2, U_1 and U_2 will remain the same. It is easy to work out the new coupling wavelength λ_0',

$$\lambda_0^{'}=R\lambda_0$$

It is also possible to work out simple formulas for calculating the temperature and strain sensitivity of the coupling wavelength, if we assume the two cores have the same strain or thermal optic coefficients and ignore the small effect on the propagation constants from U_1 and U_2 resulting from a change in V_1 and V_2. If we assume Δ_1 and Δ_2 are changed by $\partial\Delta_1$ and $\partial\Delta_2$ respectively by a change in temperature or strain, and $k=\partial\Delta_1/\Delta_1=\partial\Delta_2/\Delta_2$, the change in λ_0 can be easily worked out to be,

$$\frac{\partial\lambda_0}{\lambda_0}=-\frac{1}{2}k$$

For a change in temperature, $k=\xi_{co}-\xi_{cl}$, where ξ_{co} and ξ_{cl} are the respective thermal-optic coefficients for the core and cladding glass. In the case of strain change, $k=\chi_{co}-\chi_{cl}$, where χ_{co} and χ_{cl} are the respective effective photoelastic coefficients for the core and cladding glass. We use the thermal-optic coefficient in a 8 mol% germanosilicate glass at 1.3 μm and 250°C [7] for the core, $\xi_{co}=8.17\text{X}10^{-6}$, and for the fused silica cladding at 1.47 μm, $\xi_{cl}=1.15\text{X}10^{-5}$ [8]. This gives $\partial\lambda_0/\lambda_0=1.7\text{X}10^{-6}/°C$, i.e. 0.26 nm/100°C at 1550 nm. For silica, the effective photoelastic coefficient is χ_{cl}=-0.22. We deduced from the measurement of Bragg grating strain sensitivity in ref[9] the effective photoelastic coefficient for germanium-doped silica glass, χ_{co} =-0.23. This gives $\partial\lambda_0/\lambda_0=5X10^{-6}$ /mStrain, i.e. $7.75X10^{-3}$ nm/mStrain at 1550 nm.

For the TC fibre used, one core is placed in the centre of the fibre to facilitate splicing. The coupling wavelength of the original fibre is at 1.394 μm. The fibre has a cladding diameter of 125 μm. The tapering of the TC fibre is done on a home-made coupler rig with a butane burner and a computer controlled linear translation stage. During the tapering process, the burner traverses to and fro over a distance of up to 7 cm at a speed of 5 mm/s. The translation stage stretches the fibre at a rate of 0.05 mm/s. The process is stopped once the required elongation is reached to give a desired tapering ratio.

Only the centre part of the tapered fibre of guaranteed uniform diameter is used. It is subsequently cleaved and the centre core of the tapered TC fibre is spliced to another single core (SC) fibre. White light from a tungsten lamp is launched into the SC fibre, the output from the two cores of the TC fibre is then measured. This is done by butting the cleaved end of the tapered TC fibre to a SC fibre on a manual fusion splicer. The length of tapered TC is adjusted by subsequent cleaving to achieve a desired coupling strength of any value up to 100%. This second end of the TC fibre can then be spliced to another SC fibre. To achieve a bandpass filter, the offset core is spliced to the SC fibre. To achieve bandstop filter, the centre core is spliced.

A typical output from both cores of the TC fibre at different Rs is plotted in fig.2. It is clear that a tuning range of at least 500 nm is easily achieved. The upper limit is set by the coupling wavelength of the original fibre. The non-ideal filter response at the upper wavelength limit is due to strong OH absorption in this fibre at ~1.4 μm. The upper limit can be made to be ~1.6 μm by fibre design to cover any wavelength up to 1.6 μm. We did not attempt to make a device with coupling wavelength below 800 nm, because the low sensitivity of our measurement set-up at those wavelengths. A length of 1 to 2 cm of the TC fibre is required achieve 100% coupling and the FWHM bandwidth of the filter is typically 16 nm. The tuning curve is give in fig.3, along with the theoretical prediction in solid line.

To confirm the predicted temperature and strain stability, a filter was put in a tube furnace and was heated up to 700°C with its transmission spectrum monitored. Three such spectra at 20, 400 and 700°C are shown in fig.4, demonstrating the highly stable nature of the device operating at various temperatures, both in wavelength and strength. A slope of 0.24 nm/100°C was measured (inset in fig.4), very close to the predicted 0.21 nm/100°C at this wavelength. The transmission of a filter at zero strain and 3.3 mStrain are shown in fig.5, showing the extremely low strain sensitivity. In fact the wavelength shift is below our measurement accuracy. The estimated strain sensitivity from this measurement is below 0.075 nm/mStrain. Please note that both the temperature and strain sensitivity are much better than fibre Bragg gratings.

To summarise, we have demonstrated a novel reproducible and precise way of tuning the coupling wavelength of a mismatched twin-core filter. This allows low loss, high quality, all-fibre bandpass or bandstop filter to be implemented at any desired wavelength over a range of few hundred nanometres, from the same fibre. A ~500 nm range is demonstrated, only limited by the measurement set-up, not by the technique itself. The highly accurate control of the filtering wavelength in combination with filtering strength control by choosing the length of the twin-core fibres allows complex bandpass or loss filter to be implemented by putting several of this filters in series. These filters are also highly insensitive to temperature (~0.26 nm/100°C at 1.55 μm) and strain ($7.8X10^{-3}$ nm/mStrain at 1.55 μm), allowing easy environmental insensitive packaging. Bandwidth of the filters can be further narrowed by designing a TC fibre with larger cross angle in the propagation constant verse wavelength plot (fig.1).

Acknowledgements:

The authors would like to thank Pirelli Cavi SpA for providing the twin-core fibre used in this work.

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Figure Captions:

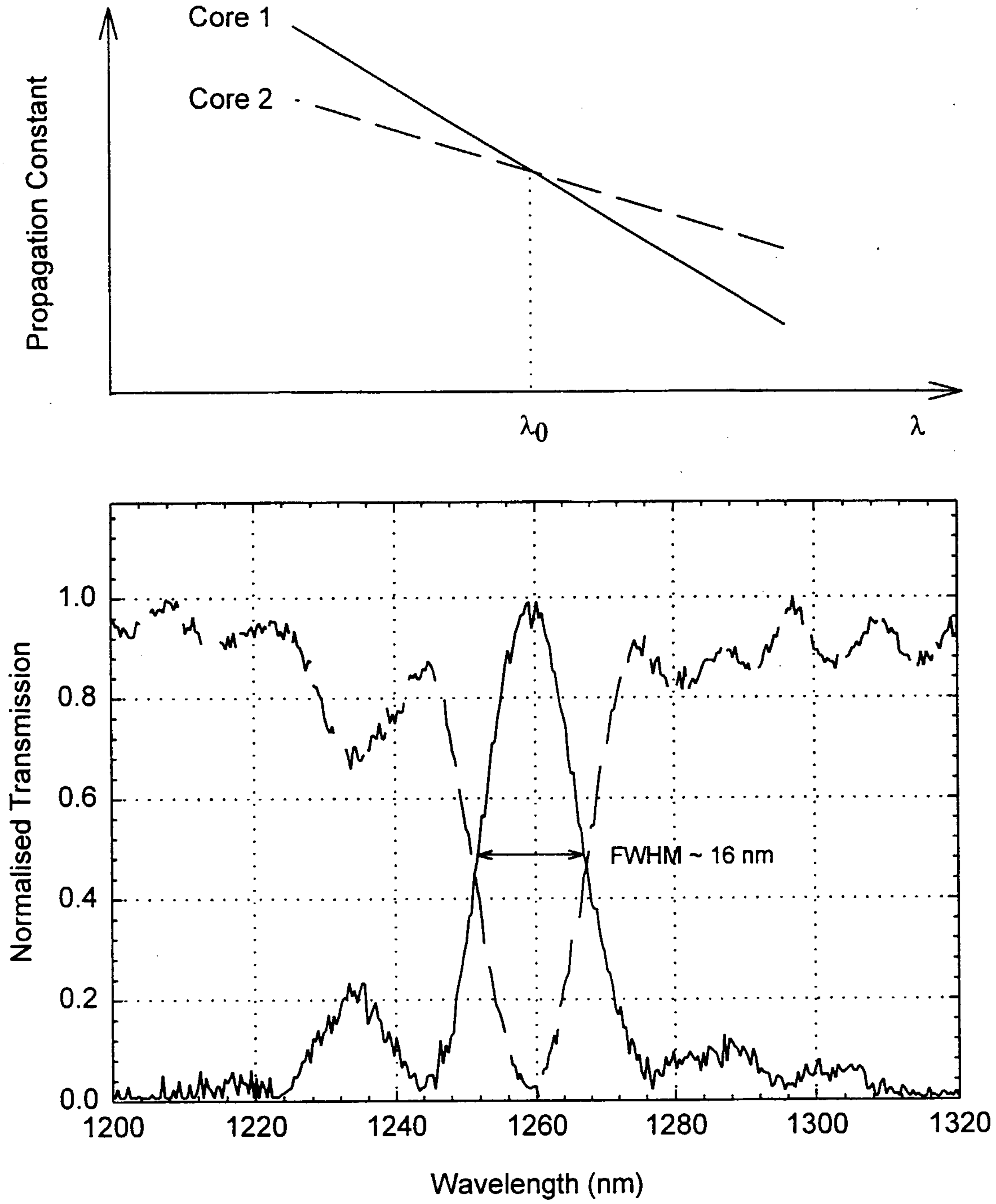
Figure 1 Schematic diagram of the propagation constants of the two cores and a typical filter response from each of the two cores when one core is illuminated.

Figure 2 Filter characteristic at various tapering ratio.

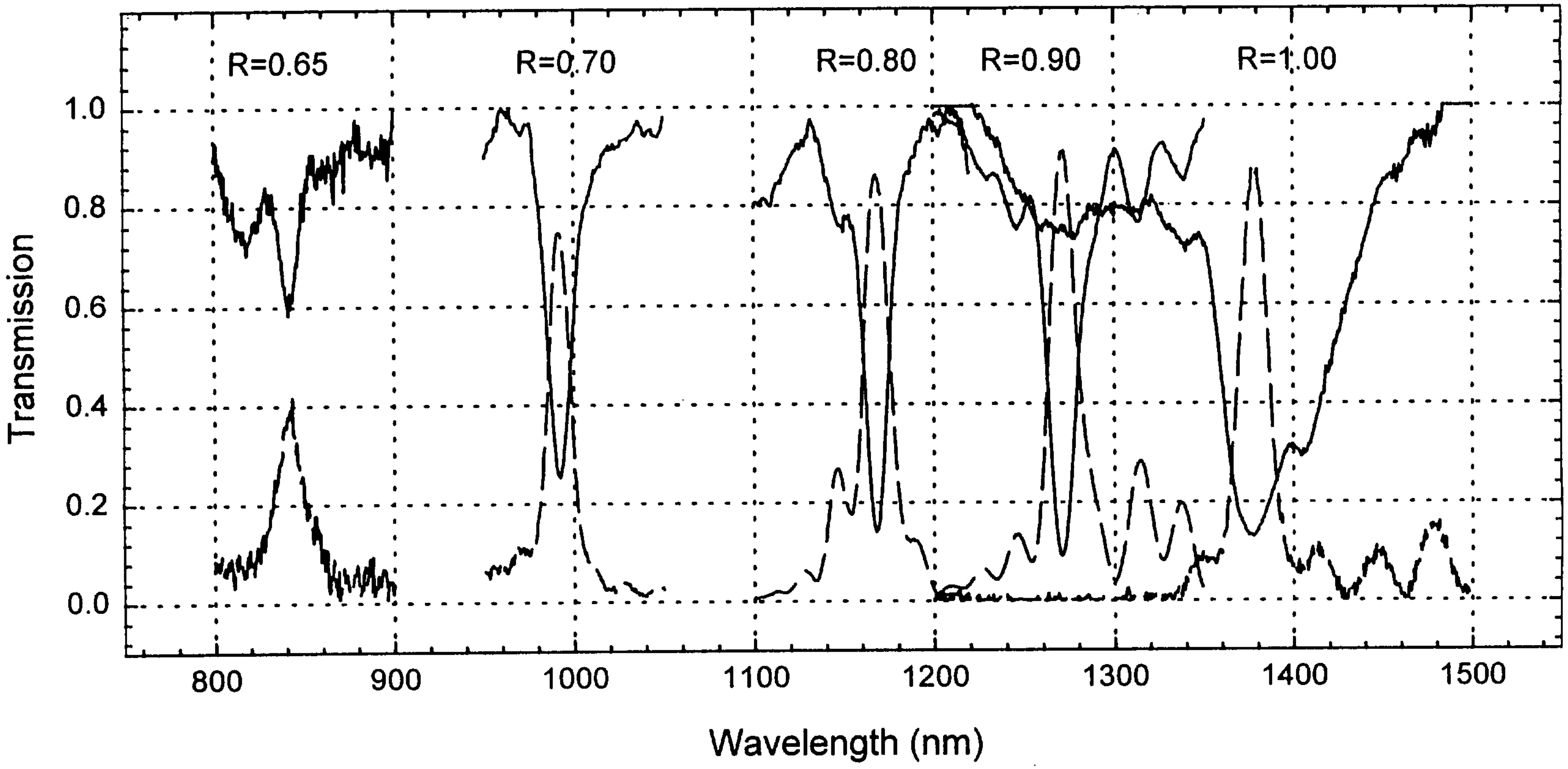
Figure 3 Tuning curve of the TC filter. The solid line is the theoretical prediction.

Figure 4 Temperature sensitivity of the TC fibre filter.

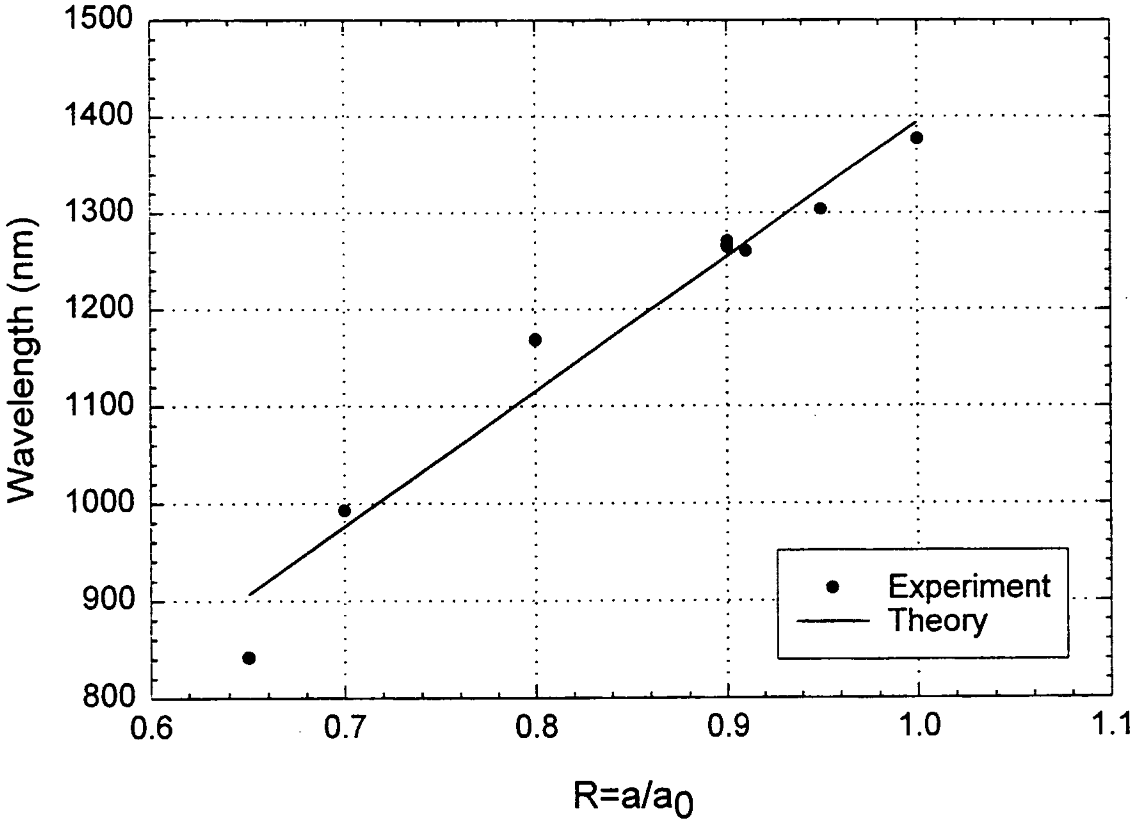
Figure 5 Strain sensitivity of the TC fibre filter. The solid line is at 3.3 mStrain and the dashed line is at 0 mStrain.



Ortega et al. Fig. 1



Ortega et al. Fig. 2



Ortega et al. Fig. 3