index difference $n_r = n_s = n_a = 1{\cdot}00$, and $n_g = 1{\cdot}50$. The aspect ratio is $w/g = 1$. The propagation constants given by the proposed method show an excellent agreement with the 'exact' values. It is clear from Fig. 4 that, the propagation constants provided by Kumar's perturbation correction method[2] still contain noticeable errors. In the very weakly guided waveguide region the proposed perturbation feedback method gives a cutoff point for the lowest order mode.

Conclusion: A simple and accurate method of waveguide analysis is presented. The proposed perturbation feedback method can provide the propagation constant of rectangular dielectric waveguides more accurately than other approximate approaches currently used. Design of integrated optical devices, composed of rectangular waveguides, could be greatly improved.

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WAVELENGTH COMBINING FUSED-TAPER COUPLERS WITH LOW SENSITIVITY TO POLARISATION FOR USE WITH 1480 nm-PUMPED ERBIUM-DOPED FIBRE AMPLIFIERS

Indexing terms: Optical fibres, Optical multiplexers

Fused-taper wavelength division multiplexing (WDM) couplers for use in combining the 1480 nm pump wavelength with the 1540 nm signal wavelength of erbium-doped fibre amplifier systems are reported. Output port isolation in excess of 15 dB has been achieved at the centre of each channel with very low polarisation sensitivity of $<0{\cdot}2$ dB over a 30 nm range about the channel centres.

Introduction: Erbium-doped fibre amplifiers operating at $1{\cdot}54\,\mu$m are of particular interest in optical communication systems because of their low interchannel cross-talk and distortion, lack of polarisation sensitivity and high fibre to fibre gain.[1,2] Practical amplifiers are expected to be pumped by laser diodes operating at either 980 nm or 1480 nm. The design of WDM couplers for the latter pump wavelength is challenging because of the close proximity of the pump and signal wavelengths. In this letter the design and construction of 1480 nm/1540 nm WDM couplers are reported with special emphasis on reducing the polarisation sensitivity of the couplers.

Design of the multiplexer: It is now well established that the fused-taper coupler operates by interference of the LP_{01} and LP_{11} supermodes of the composite structure comprising the coupler waist.[3,4] A coupler acts as a WDM when the length of the coupling region is such that no net power transfer occurs at one wavelength with complete power transfer occurring at the other. The number of coupling cycles through which the coupler must be pulled to form the multiplexer increases as the channel spacing is reduced.

Polarisation effects in fused couplers arise because of the high index difference between the cladding glass and the surrounding medium, usually air. The effects are also strongly influenced by the coupler cross-section.[5,6] In a standard 3 dB power splitter the device is usually fabricated on the first coupling cycle at which point the coupling is insensitive to polarisation. In wavelength multiplexers, the coupler must be pulled though a number of coupling cycles. This increases the likelihood of dephasing the coupling cycles between the orthogonal polarisations.[7,8] A channel spacing of only 60 nm for a 1480 nm/1540 nm WDM coupler is sufficiently small for polarisation effects to seriously degrade the performance of the device.

Polarisation effects can be reduced by lowering the index difference between the fibre cladding and the external medium or by finding an optimum coupler cross-section.

The effective-index method of coupler analysis[9] reveals that a weakly-fused coupler can be mapped onto a two-dimensional system consisting of two parallel slab waveguides separated by a small gap. Coupling is analogous to tunnelling across the gap. The dominant effect in the polarisation behaviour of these couplers is the higher tunnelling capability of TE-like waves.

In a strongly-fused coupler, no gap is predicted and the higher penetration of TE-like waves into the external medium beyond the outer boundaries of the composite waveguide leads to a lesser degree of field overlap and thus lower coupling than for TM-like waves. Polarisation effects arising from strong fusion are generally much less than those arising from tunnelling in weakly-fused couplers.

Between these two extremes an optimum cross-section exists for minimising polarisation effects. We have found that a strongly-fused dumbell structure (i.e. not quite elliptical) is ideal.

Experimental: The fibre used in the experiments had a diameter of $125\,\mu$m, a cutoff wavelength of 1450 nm and a numerical aperture of 0·20. The coupler was fabricated using the standard twist, fuse and pull technique. A white light source, a scanning monochrometer, and a phase sensitive detection system enabled the wavelength dependence of the coupler characteristics to be measured.

We describe the couplers characteristics in terms of a normalised splitting ratio, R and a normalised polarisation sensitivity, P_n. These parameters are defined in decibels as

$$R = 10\log_{10}\left(\frac{P_3}{P_4}\right) \qquad (1)$$

and

$$P_n = 10\log_{16}\left(\frac{F_x}{F_y}\right) \qquad (2)$$

where P_3 and P_4 are the output powers in the throughput and coupled ports, respectively F_x and F_y are the fraction of output power in the same port when polarised light is launched in turn along each of the principal axes of the coupler.

In fabricating the couplers it was convenient to monitor at a wavelength halfway between the two desired channels, i.e. 1510 nm. The device performance could then be related to the number of 3 dB power splitting coupling cycles at this wavelength undertaken during elongation of the coupler. We found that at the 19th 3 dB point the channel spacing was consistently within 2 nm of the 60 nm figure.

Fig. 1 shows the splitting-ratio wavelength response for unpolarised light from 1450 nm to 1550 nm for an optimally-fused coupler pulled to the 19th 3 dB point measured at

1510nm. The coupler achieved a port isolation of better than 15dB at each of the two channel centres. The high port isolation indicates minimal polarisation effects.

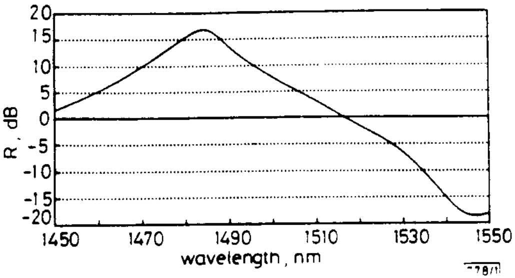

Fig. 1 *Spectral dependence of splitting ratio*

19 cycle optimally fused coupler

To illustrate the effect of the index of the surrounding medium, Fig. 2 shows the splitting ratio of a nonoptimal 22-cycle polarisation sensitive coupler both before and after encapsalation in silicone elastomer ($n = 1{\cdot}40$). After potting but before the elastomer cured the coupler was twist-tuned[10] so that there was equal splitting at 1510nm. Before potting the port isolation was limited to about 6dB because of polarisation effects. After potting, the response is similar to that of Fig. 1 indicating a reduction in polarisation sensitivity.

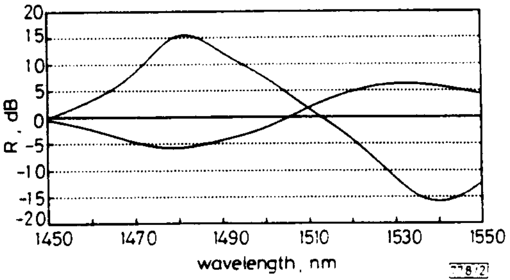

Fig. 2 *Spectral dependence of splitting ratio*

22 cycle polarisation sensitive coupler

The polarisation sensitivity of the optimally-fused and potted couplers was then measured over a 30nm band centred at 1485nm. This bandwidth corresponds roughly to that of a multimode diode laser and also to the 1dB bandwidth of the multiplexers. In performing these measurements a prism polariser was inserted between the output of the monochrometer and the launch objective lens. Wavelength scans of the power splitting over the 30nm range were then taken for each 5° increment of the polariser azimuth. The principal axis were determined as the points at which the coupling ratio was maximised and minimised at a particular wavelength. The normalised polarisation sensitivity P_n for the two couplers is shown in Fig. 3. The optimally-fused coupler has a sensitivity of <0·35dB over the whole range and the potted coupler of <0·2dB. A similar dependence was found for the 1540nm band (<0·4dB and <0·25dB for the optimally-fused and potted couplers, respectively).

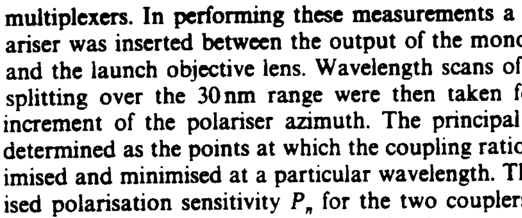

Fig. 3 *Polarisation sensitivity in 1480 mm band*

The excess loss of both couplers was <0·3dB over the entire 100nm range.

Summary: Wavelength-division multiplexers for erbium-doped fibre amplifiers pumped at 1480nm have been successfully fabricated. The 60nm channel spacing is attained at the 19th 3dB coupling cycle measured at 1510nm during elongation. Polarisation sensitivity of <0·2dB over a 30nm band has been achieved through potting in silicone elastomer and of <0·35dB over the same band by optimum fusing.

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NEWLY STRUCTURED EXPANDABLE 52-Mbit/s, 48-CHANNEL TIME-DIVISION SWITCHING LSI WITH 2·4Gbit/s THROUGHPUT

Indexing terms: Circuit theory and design, Large scale integration, Silicon, Bipolar devices

An expandable Si bipolar 2·4Gbit/s throughput, 52Mbit/s 48-channel time-division switching LSI system is described. A high-throughput of 2·4Gbit/s and a power-dissipation of 5·3W are achieved by adopting a low-voltage swing four-serial-gated differential bipolar circuit design and super self-aligned process (SST-1A) logic-in-memory LSI technology. This LSI is applicable to the digital video time-division switching and digital crossconnect systems of future B-ISDN.

Introduction: The new digital telecommunications networks require switching systems with broader bandwidths and higher bit-rate capabilities than conventional narrowband services. The time-division technique is considered difficult to apply to the switching of moving video images because of the extremely high-speed operation required because of their bit rates. Conventional switching systems and LSIs approach this problem using a space-division (SD) technique.[1,2] The time-division technique is preferable, since it is well suited to digital time-division multiplexed transmission systems.

Future video switching or digital cross-connect systems will require a switching range of about 200 to a thousand channels. Some approaches for realising a time-division (TD) switch has been reported,[3] but the switching range is still