using pseudorandom signature sequences of length $N = 127$, $E/N_0 = 20\text{dB}$ and $L = 1024$ data bits. Eqn. 2 is evaluated as a function of the normalised offered load $G = gT$ with normalised propagation delay $a = gT$ and channel load threshold $K$ as parameters. A best case value of $a = 0.01$ is used throughout.

Fig. 1: Throughput $S$ against offered load $G$ with $K$ as a parameter, $a = 0.01$

--- IP-CSSS/OD
\[ \text{slot} \] cdma

Fig. 1 shows the throughput $S$ against offered load $G$ for IP-CSSS/OD with $a = 0.01$ and $K = 10$, 15 and 20 as parameters. The throughput curve for slotted CDMA is plotted for comparison [1,5]. Fig. 1 illustrates that IP-CSSS/OD achieves a significant throughput improvement over slotted CDMA at large offered loads. The throughput increases with increasing channel load threshold $K$ until the mutual interference of signature sequences produces excessive packet failures. A value of $K = 15$ achieved the optimum throughput performance for the parameters investigated.

Fig. 2: Throughput $S$ against offered load $G$ with $a$ as a parameter, $K = 15$

--- IP-CSSS/OD
\[ \text{slot} \] cdma

Fig. 2 shows the throughput $S$ against offered load $G$ for IP-CSSS/OD with $K = 15$ and $a = 0.01, 0.05$ and 0.1 as parameters. The throughput curve for slotted CDMA is plotted for comparison. Fig. 2 illustrates that the throughput improvement in IP-CSSS/OD at high offered loads is due to channel sensing with overload detection and that this strategy is most effective in LANS with a small normalised propagation delay.

Conclusions: The throughput performance of a new IP-CSSS/OD protocol has been analysed and compared with slotted CDMA for identical channel conditions. The analysis provides a new method for evaluating throughput in SSMA schemes. IP-CSSS/OD achieves a significant throughput improvement over CDMA at large offered loads. When throughput and offered load are normalised to the channel operating bandwidth (i.e. $S/N$ and $G/N$), to compare dissimilar multiple access schemes, then at high offered loads IP-CSSS/OD uses the channel more efficiently than ALOHA whereas CDMA does not. The IP-CSSS/OD protocol may be applied to packet radio networks, indoor wireless LANs and CDMA cellular mobile networks using an ISMA scheme.

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Wideband 32 × 32 star coupler module with gain

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Indexing terms: Fibre lasers, Optical couplers, Star couplers

A wideband 32 × 32 star coupler module using two fibre amplifiers is presented. Not only can the loss of this module be fully compensated for but also it has better loss uniformity. The power margin increment of 18 dB is achieved with this module in a 1.7 Gbit/s system experiment.

Introduction: Large $N \times N$ fibre-optic star couplers play a central role in the architectures of many high-throughput multiple-access WDM networks. However, its inherent $1/N$ splitting loss may limit the ultimate size of the star coupler. Potential use of erbium-doped fibre (EDF) amplifiers to increase the number of users that a fibre-optic star network can support has been investigated by many researchers [1-5]. The number of EDF amplifiers and the choice of their locations in the star network decide the complexity and cost of the network. Among these configurations, the complexity and cost of the proposed scheme in [5] are so far less than those of other configurations. In this Letter, a 32 × 32 star coupler module based on the principle in [5] is constructed and investigated. The power margin increment of 18 dB is achieved with this module in a 1.7 Gbit/s system experiment.

Description of module: The schematic diagram of the 32 × 32 star coupler module is shown in Fig. 1a. It is composed of two 16 × 1 tree couplers, a 2 × 32B coupler, four optical isolators, two EDF amplifiers in forward pumping scheme and two 1 × 16 tree couplers. Here, these two 16 × 1 tree couplers used are for study, which should be replaced by two 16 × 1 WDM multiplexers in WDM applications. The total passive loss of this module varies somewhat with the channel used and has an average value of $-31 \text{dB}$ (14 dB before the EDF and 17 dB after the EDF) in which the loss of EDF is not included. It is this loss we would like to fully compensate for with two EDF amplifiers. The home-made EDF had a core size of $4.2 \mu m$ and an NA of 0.23. There are two $0.98 \mu m$ pump laser diodes in this module; each pump laser with $50 \text{mW}$ output power is efficiently coupled into the $12.3 \mu m$ EDF by a $0.98(1.55) \mu m$ WDM coupler. The dimension of this 32 × 32 star coupler module as shown in Fig. 1b is $32 \times 20 \times 40 \text{cm}$, which can be reduced to a more compact size with some care of arrangement. In the experiment, a pigtailed 1.550 nm DFB laser transmitter is directly modulated by a 1.7 Gbit/s (2^11 - 1) NRZ pseudorandom data stream and the receiver used is composed of a 0.4 nm optical bandpass filter and an avalanche photodiode, which has $-35.7 \text{dBm}$ sensitivity for 10^10 bit error rate (BER) at 1.7 Gbit/s.

References

Performance of module: Fig. 2 shows the spectral loss characteristics of this module for a single input channel with four different input signal powers. The small-signal system net gain at 1530 nm is slightly higher than that at 1550 nm. Note that the variations of system loss are less than 2.0 dB for $P_i = -3$ dBm in the spectral range from 1528 nm to 1565 nm. The system loss of this module can be fully compensated when the input signal power is less than $-10$ dBm. The measured system saturated output signal power of this module is $46$ dBm. This output signal power is approximately equal to the total saturated output power expected for multichannel applications. Further improvement of the saturation power may be achieved by using a more efficient EDF or increasing the pump power. Furthermore, the uniformity property of system insertion loss of this module is less than 1.3 dB.

The system sensitivity of this module for $10^{-9}$ BER at 1.7 Gbit/s is $-35$ dBm at 1550 nm, and there is $-0.7$ dB power penalty due to the amplified spontaneous emission (ASE) noise resulting from these two activating EDF amplifiers with the transmitter input power of $-15$ dBm. Fig. 3 shows the power penalty and power margin increment of this module for a single channel at 1550 nm. The lower input power level into this module the higher power margin increment, which is due to the large nondepleted ASE noise with respect to smaller input signal power. The power margin increment is defined as the power margin enhancement at $10^{-9}$ BER of this amplified module over a passive 32 x 32 star coupler with $-174$ dB insertion loss. The increment is contributed by the compensated module loss and power penalty of the transmitting signal. There is an increment of about 18 dB for input powers in the range $-19$ to $-13$ dBm; however, this power margin decreases for input power levels beyond this range. Fig. 4 shows the spectral characteristics of power penalty and power margin increments of this module for a 1550 nm input signal at channel 1 with a $P_i$ of $-15$ dBm and the input channel 2 (namely crosschannel) at various wavelengths with an input power of 15 times that of channel 1. The power margin increment is larger than 12 dB and the power penalty is less than 0.6 dB in the spectral range 1520-1570 nm.

Conclusions: We have presented a 32 x 32 star coupler module using two EDF amplifiers. The pump power use efficiency of this module (i.e. 32 port/100 mW) is, to our knowledge, the highest yet reported. Not only can the loss of this module be fully compensated over a wide spectral range, but also has better loss uniformity, low power penalty and high power margin increment. The demonstration of this proposed technique makes feasible the construction of a large star coupler for widespread star networks.

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Accurate physical fusion taper shape model for waveguide analyses

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Indexing terms: Optical fibre fabrication, Optical couplers

A model for predicting the accurate shape of fusion tapers depending on fabrication parameters has been developed and applied to the sensitive tapering of DC fibres resulting in short low-loss tapers.

Introduction: Thermally tapered fibre-optic devices such as couplers, wavelength division/multiplexers and micro-ring resonators require an accurate understanding of the relationship between technological and device parameters. No exhaustive theoretical model is available which considers technological parameters and relates them to the characteristics of fused optical components. For example, fusion couplers have been analysed by using either the mean fibre diameter or a linear or exponential approximation for the taper geometry [1, 2]. Empirical studies of the pulling process of taper couplers have been supported by [3], which related gas flow parameters to diameter variations approximated by a second order polynomial, provided a more accurate model but still lacked generality.

This Letter describes an accurate method for analytically determining the shape of thermally tapered fibres. Thus the model establishes the relationship between the technological parameters of elongation, pulling speed and temperature distribution and the resulting taper geometry. The diameter variation is determined for optimizing taper geometries as one typical application example. Compared to matched-cladding (MC) fibres which are usually used for fused taper devices, depressed-cladding (DC) fibres need very smooth taper structures [4] that would normally result in impractical taper lengths of the order of half a metre or more. However, using the model presented in this Letter it has been possible to predict and manufacture shaped tapers from DC fibres which are comparable to MC fibres in terms of taper length and losses.

Theory: The process of pulling glass fibres in the range of their softening temperature (i.e. log $\eta$ = 7.6) can be described by

$$\frac{d (\frac{L}{A})}{dt} = K \cdot \frac{F}{A}$$

where $L_i$ is the relative elongation, $F$ is the pulling force, $A$ is the fibre cross-section and $K = (3\eta^3)$ [5] is a constant related to viscosity $\eta$.

By quantitizing to m volume elements $V_i$ of any small size which is shown in Fig. 1, a description of the diameter variation at any fibre position can be developed where

$$V_i = \frac{V}{m} = \frac{\pi}{4} \cdot d_i^2 \cdot l_i$$

If the fibre is fixed on one side then the overall pulling speed $V_f$ results from the sum of the individual elongation speeds. For a taper process that makes use of two moving jigs the overall pulling speed would result from a vectorial summation of the jig velocity, thus

$$v_f = \sum_{i=1}^{m} v_i$$

Comparing this approach with the well known serial connection of spring elements in mechanical engineering we can assume a constant drawing force at any volume element. Therefore eqn. 4 holds.

$$v_i = \frac{\Delta l_i}{\Delta t} \approx F \cdot \frac{l_i}{3\eta\cdot A_i}$$

Normalising gives a coefficient ranging from 0 to 1 which yields the individual elongation speed $v_i$ after multiplication with the overall pulling speed $v_f$ described by

$$v_i = \frac{\Delta l_i}{\Delta t} \cdot v_f$$

Thus the elongation of any volume element $t_i$ during a time interval $\Delta t$ can be calculated which yields the new diameter, respectively, because of the volume constancy.

$$d_i = \sqrt{(l_i + \Delta l_i)}$$

Because the viscosity of silica glass is related very closely (+3K) to the applied temperature due to the Vogel-Fulcher-Thompson equation [6] the diameter variation of the tapered fibre can be determined in terms of the elongation, the pulling speed and the temperature distribution.

$$v_f = \frac{w_{max}}{\sum_{i=1}^{m} 3\eta\cdot A_i}$$

The validity of the model follows for the following conditions:
(i) The volume of the fibre is constant (i.e. thermal expansion can be neglected).
(ii) The impact of flame pressure and gravity can be ignored because they have to be excluded anyhow by means of relatively low tapering temperatures (<2000°C) in order to avoid losses due to micro-bending.
(iii) The influence of the surface tension can be neglected because of the mentioned low tapering temperature (the forces caused by surface tension on a taper volume element are typically two magnitudes below those due to the pulling process, thus no improvement has been achieved).

Calculating the local diameter and hence the local core radius variation $d_{max}$ yields the essential parameter for evaluating possible losses due to launching of higher order modes. Thus an immediate comparison with the allowed phase differences of the $HE_{10}$ and typically the $HE_{20}$ mode of the coaxial waveguide in the case of DC fibres can be carried out [4] because

$$\frac{da}{dz} < a \frac{\beta_{HE_{10}} - \beta_{HE_{20}}(HE_{11}max)}{2\pi}$$

Experiment: A specific burner with 13 individually controlled nozzles provided the capability of a wide variety of temperature profiles over a 20mm range. Based on a temperature distribution with a 1930°C dip at the edges of the burner and a smooth 1820°C central dip, a constant pulling speed of 26μm/s and an elongation of...