frequency response for the illuminated photodiode and the receiver. The gain flatness in the passband is within $\pm 0{\cdot}25$ dB.

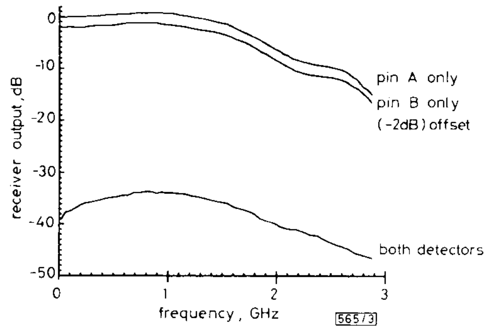

Fig. 3 *Frequency response of receiver and noise cancellation*
Illumination $\lambda = 1{\cdot}3\,\mu$m, coupler 49·4 : 50·6, overall QE mismatch 1·2%

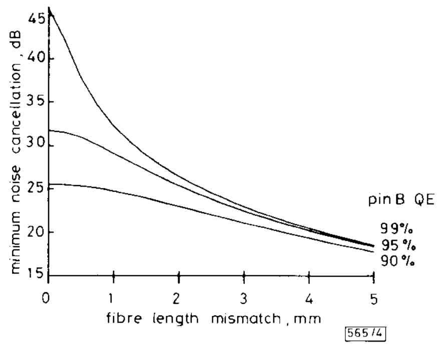

Fig. 4 *Minimum noise cancellation for 565 Mbit/s dual-detector receiver*
Directional coupler 50 : 50, bandwidth 1·75 GHz, photodiode A 100% QE

This measurement was repeated for the other photodiode to demonstrate that any small asymmetry in the photodiode bonding arrangement does not affect performance. The receiver has a bandwidth of 1·75 GHz which is sufficient for 565 Mbit/s DPSK heterodyne operation with the IF at 1·5 times the bit rate.

565 Mbit/s DPSK heterodyne system experiment: The balanced receiver reported here was used in a 565 Mbit/s optical fibre DPSK heterodyne system experiment at a wavelength of $1{\cdot}5\,\mu$m. Because of its low-noise performance and gain flatness it achieved the highest sensitivities to date[3] of $-51{\cdot}9$ dBm at a bit error rate of 10^{-9}. This represents an improvement of 4·3 dB in a previously reported BT field trial system[2] using this receiver. With a LO power of 1 mW, produced from a long external cavity source, the thermal noise penalty for the receiver was only 0·7 dB.

Conclusions: A high-performance balanced dual-detector receiver which uses a low-noise GaAs IC transimpedance preamplifier has been developed for a 565 Mbit/s optical fibre DPSK heterodyne system. This has achieved a sensitivity of $-51{\cdot}9$ dBm, the best reported value at this bit rate, improving the sensitivity of a previously reported BT field trial system by 4·3 dB. The accurate matching of QE from the coupler to the photodiodes can lead to a cancellation of at least 34 dB of LO excess intensity noise with a return loss of >60 dB. It has been shown that GaAs IC integration of the receiver preamplifier can provide performance superior to that of discrete hybrid preamplifiers, which use smaller gate geometry devices, and has the advantage of much lower manufacturing costs. The reproducibility associated with an IC technology would be important for the realisation of coherent multiport receivers.

Acknowledgment: Acknowledgment is made to the Director of Research and Technology of British Telecom and the Directors of BT&D Technologies Ltd. for permission to publish this paper. We also wish to acknowledge the contribution of D. Wake for fabrication of the photodiodes, C. M. Carson for assembly of the receivers, J. Lowe and A. Hare for IC layout, and H. King and B. R. White for assisting with receiver measurements.

P. P. SMYTH
A. A. SAYLES
N. R. BACK
A. P. McDONNA
M. J. CREANER

25th July 1989

British Telecom Research Laboratories
Martlesham Heath, Ipswich IP5 7RE, United Kingdom

References

1 KASPER, B. L., *et al.*: 'Balanced dual-detector receiver for optical heterodyne communication at Gbit/s rates', *Electron. Lett.*, 1986, **22**, (8), pp. 413–414
2 CREANER, M., *et al.*: 'Field demonstration of 565 Mbit/s DPSK coherent detection transmission system over 176 km of installed fibre', *Electron. Lett.*, 1988, **24**, pp. 1354–1356
3 MEISSNER, E.: '116 photons/bit in 565 Mbit/s optical DPSK heterodyne transmission system', *Electron. Lett.*, 1989, **25**, pp. 281–282

UNBALANCED DISSIMILAR-FIBRE MACH-ZEHNDER INTERFEROMETER: APPLICATION AS FILTER

Indexing terms: Optical fibres, Optical filters, Interferometers, Optical connectors and couplers

An unbalanced Mach–Zehnder interferometer made using dissimilar-fibre fused taper couplers is proposed for filtering applications. The all-fibre device is compact, rugged, simple to make and provides extended control and flexibility for the design of various types of filters.

Introduction: In this letter we report compact, fibre-based, unbalanced Mach–Zehnder interferometers fabricated from dissimilar-fibre fused couplers.[1] Compact, balanced, similar-fibre Mach–Zehnders have been reported before.[2] Unbalanced Mach–Zehnder interferometers are very flexible in their design for the practical synthesis of optical waveguide filter characteristics. We describe the unbalanced interferometer design and the interplay of the component parts; we also present experimental results.

Interferometer design: A diagram of the proposed Mach–Zehnder is shown in Fig. 1. The Mach–Zehnder is fabricated

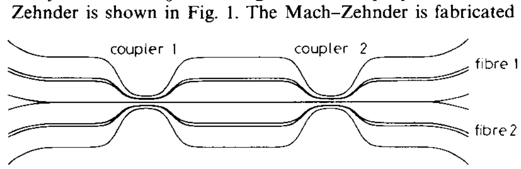

Fig. 1 *Unbalanced dissimilar-fibre Mach–Zehnder*

by fusing two fibre strands laid parallel and in contact with each other over a length long enough to permit fabrication of the two couplers at each end of the interferometer. The resulting device has two input and two output ports. The interferometer arms between the couplers are of equal physical length. However, the optical path lengths of the two arms are different because the two fibres fused together to make the interferometer are dissimilar and therefore have different propagation constants.

The device differs from conventional Mach Zehnders in that the splitting ratio of the two couplers used to divide and recombine the signals is not constant (3 dB splitting) with wavelength, but varies sinusoidally. As a result, the relative amount of light in the two arms changes with the optical wavelength. Furthermore, the three component parts of the interferometer can be designed quite independently from each other. As a consequence, it is possible to exploit each component's wavelength response to achieve a variety of different wavelength responses for the interferometer as a whole. For example, each coupler can be fabricated with any number of power transfer cycles within a wide range of different taper profiles. Control of the taper profile provides a means for controlling the relative positions of the core-mode cutoff locations ($V_{core} = 1$) in the two fibre tapers, affecting the path length difference.

The fabrication of the unbalanced Mach–Zehnder interferometer requires the capability to form fused couplers from pairs of dissimilar fibres. The condition under which suitable fused dissimilar-fibre couplers can be made is not known quantitatively. It has been shown, however, that with some combinations of dissimilar monomode fibres, fused couplers can be made using the simple fuse-pull-and-taper technique.[1,3] With other fibres, etching of the cladding[4] or prestretching of one of the fibres is required during the fabrication process to achieve coupling.

Experimental results: A number of Mach–Zehnders were fabricated to illustrate the range of possibilities available with this configuration. In particular, we have concentrated on identical, one-power-transfer-cycle couplers (two coupling lengths at the fabrication wavelength of 1·15 μm) made from Corning fibres with cladding diameters of 125 μm, core diameters of 8 μm and 4·5 μm and cutoff wavelengths of 1·1 and 0·8 μm, respectively. To permit these two fibres to couple completely even with a small degree of fusion at the fabrication wavelength of 1·15 μm, the 1·1 μm cutoff fibre has to be prestretched before fusion. After fusion, two couplers are pulled successively leaving a predetermined length for the central part of the interferometer.

Fig. 2 shows the measured and calculated wavelength response of the coupling ratio (the ratio of coupled port power over the sum of the powers from both output ports) when white light is launched into one input port of a Mach–Zehnder. In Fig. 2*b* the calculation takes into account the amplitude and phase wavelength response of the couplers and of the path length difference. Two distinct waveforms contribute to this wavelength response. The slow envelope modulation with minima of 1·1 and 1·5 μm is the contribution of the fused couplers. The rapid oscillations which are chirped with wavelength result from the optical path length difference. When both couplers are identical, as is the case in Fig. 2, the modulation envelope is a sine wave with a period determined by the number of power transfer cycles during fabrication. On the other hand, the path length difference depends on the type of fibre used, the length between couplers and the locations of the $V_{core} = 1$. This Mach–Zehnder can be used as a multiplexer/demultiplexer for wavelength division multiplexing (WDM) at 1·3 and 1·5 μm. The excess loss is typically 1 dB.

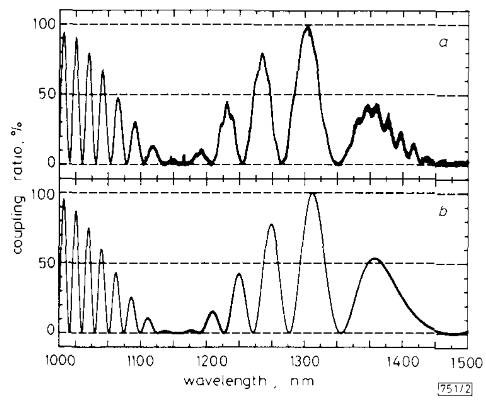

Fig. 2 *(a) measured and (b) calculated coupling ratio against wavelength for Mach–Zehnder made from identical 1-cycle couplers with 53 mm spacing between coupler centres*

Fig. 3 shows the spectral response of two cascaded unbalanced Mach–Zehnders. Both Mach–Zehnders are formed from identical one-cycle couplers and are cascaded by splicing together the coupled output fibre of the first to the input fibre (same type) of the second. The two interferometers differ only in the length of their central spacing. Again white light is launched into one input port of the first Mach–Zehnder, and the trace is the output power from the coupled port after the second Mach–Zehnder. The contribution of the first is the slow envelope modulation with a period of 50 nm. The second, with a long central spacing, generates the rapid oscillations of 2 nm periods. The result shows the potential of these devices to extract closely spaced wavelengths from a comb of wavelengths in frequency division multiplexing networks.

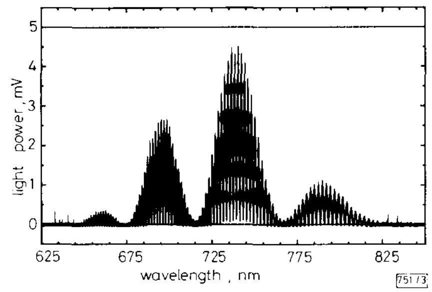

Fig. 3 *Output power of coupled arm for two cascaded Mach–Zehnders with central spacing 26·5 mm and 105 mm between coupler centres*

The wavelength characteristic of the unbalanced Mach–Zehnders can be altered simply by applying heat, pressure, or tension to the central part of the device. Also, we can anticipate that the unbalanced fibre Mach–Zehnder may, under high-power illumination, exhibit different intensity dependent refractive index changes in the two fibre interferometer arms that will result in switching the light between the two output ports.

Conclusion: Compact unbalanced fibre Mach–Zehnders with excess loss typically ≃ 1 dB are reported and their wavelength dependence measured. The devices are suitable for mounting in small rugged packages. The design of the devices is also highly flexible; a variety of different wavelength responses are possible. Thus, the devices may find application as filters or as wavelength multiplexer/demultiplexers.

Acknowledgment: We thank George Berkey and Allan Morrow of Corning Inc. Research and Development Laboratories for providing some of the spectral fibre for this work.

21st August 1989

B. MALO
F. BILODEAU
K. O. HILL
D. C. JOHNSON
J. ALBERT

Communications Research Centre
PO Box 11490, Station 'H'
Ottawa, Ontario, Canada K2H 8S2

References

1 BILODEAU, F., JOHNSON, D. C., FAUCHER, S., and HILL, K. O.: 'Monomode fiber fused-taper couplers: Applications as sensors, tunable filters and lateral splices'. SPIE, 1988, **988**, pp. 2–10

2 SHIPLEY, S. P., GEORGIOU, C., and BOUCOUVALAS, A. C.: 'Compact all-fibre Mach–Zehnder devices', *IEE Proc. J*, 1987, **134**, (3), pp. 203–207

3 BIRKS, T. A., and HUSSEY, C. D.: 'Behaviour of asymmetric fuse-tapered single-mode fibre couplers'. IEE colloquium on all-fibre devices, 3rd June 1988, digest no. 1988/90, pp. 211–214

4 LAMONT, R. G., HILL, K. O., and JOHNSON, D. C.: 'Tuned-port twin biconical-taper fiber splitters: fabrication from dissimilar low-mode-number-fibers', *Opt. Lett.*, 1985, **10**, (1), pp. 46–48