with asymmetrical refractive index pits on both sides of the core were investigated. It was shown from the measurement that the beat length was about \( L = 23 \) mm (birefringence \( \beta = 5 \times 10^{-5} \)) and the state of linear polarisation of the initiating light beam was maintained up to 0.6 kg/cm² of the concentred force when the incident plane of polarisation was coincident with the major axis of the fibre. It was also shown that the degree and the plane of polarisation were scarcely influenced by the ambient conditions such as temperature variations from 20°C to 100°C, and twists of the fibre. The extinction ratio of the fibre was greater than 30 dB.

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BACKSCATTERING MEASUREMENT OF BENDING-INDUCED BIREFRINGENCE IN SINGLE MODE FIBRES

Indexing terms: Optical fibres, Birefringence, Polarisation

The local distribution of birefringence in a very low birefringence single mode fibre less than 1 km long is measured by analysing the backscattered light. The experimental results of bending-induced birefringence measurements for various bending radii are in good agreement with those calculated. For 130 µm diameter fibre wound around cylinders of radii 15 cm and 8 cm, the bending-induced birefringence \( \beta_b(15 \text{ cm}) = 9°/\text{m} \) and \( \beta_b(8 \text{ cm}) = 34°/\text{m} \), respectively, at \( L = 904 \text{ nm} \).

Single mode fibres are becoming of increasing interest because of their applicability in various fields, including wide bandwidth optical communication, optical fibre rotation sensing,\(^1\) current monitoring\(^2\) and other interferometric devices.\(^3\) The satisfactory operation of such devices relies on the stability of the polarisation state of light propagating along the fibre.\(^4\) For this reason, there have been considerable efforts to understand the influences of various kinds of perturbations such as bending,\(^5\) twisting,\(^6\) lateral stress\(^7\) etc. all of which are unavoidable in any real installed fibre. All this work has been done with rather short fibre samples (1–2 m) prepared with great care to ensure that there are no ambiguous effects other than those to be measured. In any practical system, the length of fibre is not so short and perturbations may not be simple as light propagates along the fibre. In this letter, we report that the backscattering method is successfully applied to measure the spatial distribution of birefringence and to locate the irregularities of polarisation properties along the length of single mode optical fibres. The experimental results of the bending-induced birefringence measurements for an extremely low birefringence single mode fibre are also presented.

In a single mode fibre, the birefringence \( \beta \) becomes \( \beta = k_x - k_y \), where \( k_x \) and \( k_y \) are the propagation constants of light polarised along the mutually orthogonal fast and slow axes \( x \) and \( y \), respectively. Let \( z \) be the distance along the fibre from the input end. Linearly polarised light launched into a fibre at \( z = 0 \) is continuously Rayleigh scattered as it propagates along the fibre, and part of the scattered light is guided back to the launch point \( z = 0 \). During the backscattering process, the polarisation state of the light is conserved.\(^1\) The backscattered signal from point \( z \) in the fibre can be represented, in general, by

\[
E_b(z) = [ia \cos (\omega t - 2k_x z) + jb \cos (\omega t - 2k_y z)] \exp (-2z) \quad (1)
\]

The backward light wave is redirected at a polarising beam splitter to the detector (Fig. 1), and the detected light intensity becomes, after averaging over one period,

\[
I_b(z) = C(a, b) \exp (-2z) \sin^2 \{k_x - k_y\}z \quad (2)
\]

where \( C \) is a constant determined by \( a \) and \( b \). The period of this sinusoidal variation depends on the birefringence \( \beta \); it is

\[
\Delta z = \pi/\beta = L_b/2 \quad (3)
\]

where \( L_b \) is the beat length of the fibre. In this way, the birefringence intrinsic or induced can be measured directly by OTDR.

The elements of the OTDR for measuring birefringence are shown in Fig. 1. The apparatus used in this experiment is similar to that used for ordinary OTDR,\(^12\) except that the polarising beam splitter is used in place of a beam divider. A pulse of light with 10 ns half width is launched into a single mode fibre after being linearly polarised by a polarising beam splitter. The peak power of the pulse is about 1 W and the repetition rate is 10 kHz. Of the backscattered signal, the linear polarising beam splitter is used in place of a beam divider. A pulse of light with 10 ns half width is launched into a single mode fibre after being linearly polarised by a polarising beam splitter and APD photodetector. The single mode optical fibre under test is a fibre of extremely low birefringence whose core and cladding composi-
and eqn. 2 (curve b). Good agreement can be seen with respect to periodicity and sinusoidal behaviour.

The periods of these signals are obtained through Fourier analysis of the OTDR signals of a single mode fibre, showing bending-induced birefringence for different bending radii. The fibre, of length 260 m, was wound around drums of 15 cm and 8 cm bend radius. For each case there is a large peak at the launch point, whose tail extends over a considerable length. This is due to the reflectance from lens surfaces at the launch end face of the fibre. At the far end there is also a peak, which is a reflection signal from the end face. Between these peaks, backscattered signals which are sinusoidal with respect to the position along the fibre are seen, as predicted in eqn. 2. For 15 cm bend radius, the period of the sinusoidal variation is about 20 m, and according to eqn. 3, the birefringence \( \beta_b \) is 9°/m. For 8 cm bend radius, a great deal of bending loss can be seen; the period is about 5-3 m, which corresponds to birefringence \( \beta_b = 34°/m \).

fig. 2 OTDR signals of a single mode fibre, showing bending-induced birefringence for different bending radii
(a) 15 cm bend radius
(b) 8 cm bend radius (note considerable bending losses)

The periods of these signals are obtained through Fourier transformation of the signal patterns. The bending induced birefringence for 15 cm and 8 cm bend radii should be 10°/m and 36°/m, respectively,7 for 904 nm wavelength and 130 \( \mu \)m fibre diameter. The experimental results in Fig. 2 are in good agreement with the theory developed in Reference 7, and eqns. 2 and 3 are well verified in this respect.

Inserting into eqn. 2 the scattering coefficient \( (\alpha = 1 \times 10^{-3}/m) \) corresponding to a loss of about 4.3 dB/km and \( k_e = k_o = 9°/m \), we obtain a sinusoidal curve matching the OTDR signal at 15 cm bend radius. As we can see in Fig. 3, the minimum level of the backscattered sinusoidal signal does not drop to zero, contrary to the theoretical prediction. This discrepancy is probably due to the tail of the first peak and to imperfect mode stripping. The periodic behaviour of the backscattered signal is, however, almost exact in Fig. 3, and we obtained some important information about the polarisation properties of the fibre, such as the uniformity of polarisation properties along the fibre and the bending-induced birefringence.

In conclusion, a novel method is applied to measure directly the spatial distribution of polarisation properties along a long single mode fibre using OTDR, and this is verified through bending-induced birefringence measurements. This technique is very promising in various fields of single mode fibre applications where the polarisation property of the fibre is important. With a shorter light pulse and a wider bandwidth detection system, it can be applied to fibres of higher birefringence, and more information on polarisation properties may be obtained.

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**VOLTAGE AMPLIFICATION IN SWITCHED-CAPACITOR NETWORKS**

*Indexing terms: Switched capacitor networks, Amplifiers*

The letter deals with the voltage amplification property of networks containing only capacitors and switches. It is shown that with any given \( n \) capacitors a circuit comprising a finite number of switches may be realised for which a voltage amplification close to 2\( n \) is achievable. If there is freedom in choosing the capacitors, then a switching circuit may be designed for which voltage amplification close to \( 2^{n+1} + 2^{n-1} \) is achievable. It is conjectured that this number presents the upper bound of voltage amplification achievable by means of an SC circuit with \( n \) capacitors.

**Introduction:** Recent advances in MOS integrated circuit technology have produced a growing interest in switched capacitor circuits. Systems containing only capacitors belong to a family of one-kind-element networks, and share with all members of that family the so-called no-amplification property. It has been shown that, if an energy source is applied to such a network, then the voltage between any pair of its vertices or the current in any of its edges cannot exceed in magnitude the input voltage or current, respectively.1 Adding switches to such a network results in a structure which may be capable of voltage