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Rigorous analysis of form birefringence of fused fibre couplers

T.-L. Wu and H.-C. Chang

Indexing terms: Optical couplers, Optical fibre theory

The influence of the degree of fusion on the form birefringence of fused optical fibre couplers is investigated based on a rigorous vectorial analysis using the surface integral equations method. Form birefringence against aspect ratio of the coupler cross-section for different normalised frequencies V are calculated. It is found that the birefringence is also significant as the degree of fusion approaches 2.0.

Introduction: It is well known that fused fibre couplers can be designed for polarisation beamsplitting [1–5]. In the neck region of the coupler the shape of the cross-section is dumbbell-like. This dumbbell-shaped cross-section has been modelled as a rectangular [3, 6] or an elliptical region [7, 8]. It has been shown that for polarisation beamsplitting the fused coupler with large V-value is well modelled by an elliptical cross-section but not by a rectangular one [4] because there is an isotropic point (equal coupling coefficients for x and y polarised lights, $C_x = C_y$) at some degree of fusion for the elliptical model but there is none for the rectangular model. However, for couplers with longer elongation the V-value in the waist region would not be large. It is thus necessary to study the birefringence behaviour of the fused coupler with smaller V-values.

Zheng analysed the dumbbell-shaped structure and predicted that the fused coupler is isotropic when the degree of fusion is 1.8 [8]. In his investigation, by assuming that the V-value of the fused coupler is large, the asymptotic forms of modal propagation constants were derived [7] and the finite-element method was used to solve the coupling coefficients for the two polarisations.

In this Letter, based on a full-wave vectorial formulation, the surface integral equation method [9] is used to solve the propagation constants of two polarisation states for the fused coupler with dumbbell-shaped cross-section. The influence of the degree of fusion on form birefringence of the coupler is investigated both for couplers with small V-value ($V = 8$) and for those with large V-values ($V = 40$ and 70). We have found that for the coupler with large V-value the isotropic point occurs at the aspect ratio of 1.8 as Zheng predicted, but for the coupler with small V-value, $C_x - C_y$ may not change sign as the degree of fusion varies from 1 to 1.95. The transition of the isotropic point of the coupler with V value varying from 8.5 to 40 is also presented.

Analysis and results: Inset in Fig. 1 are the dumbbell-shaped cross-section and the co-ordinates of the fused coupler, where $2d$ is the major width of the coupler, r is the radius of the reduced fibre cladding, and n_1 and n_2 are the refractive indices of the coupler and the surrounding medium, respectively. Here, $n_1 = 1.45$ and $n_2 = 1$ are chosen because in the neck region of the coupler the light is strongly guided by the boundary between the fibre cladding and the external medium which is air unless some other potting material is employed. The degree of fusion, or the aspect ratio, is defined as d/r. When $d/r = 2$, the fibres are weakly fused and just touching; when $d/r = 1$, the cross-section is circular. The form birefringence is defined by

$$B = \frac{rV^2}{\Delta^{3/2}}(C_x - C_y) \qquad (1)$$

where $V = (2\pi/\lambda)r\sqrt{(n_1^2 - n_2^2)}$ is the normalised frequency, $C_x = (\beta_{even}^x - \beta_{odd}^x)/2$ and $C_y = (\beta_{even}^y - \beta_{odd}^y)/2$ are the coupling coefficients of the x and y polarised lights, respectively, with βs being the propagation constants, and $\Delta = (n_1^2 - n_2^2)/2n_1^2$. Owing to the geometrical symmetry of the dumbbell shape, division is carried out over only one-fourth of the boundary in the surface integral equation method. When the waveguide aspect ratio is close to 2.0, the node points near the touching regions are very close to one another, causing singular problems for the Green functions in this method. Such situations need some finer numerical evaluation and will not be discussed here. The propagation constants of the even and odd modes for the two polarisations can be obtained in ~5min on a PC-486 computer. Fig. 1 shows C_x and C_y as functions of the aspect ratio for three different V-values. The coupler with large aspect ratio is weakly fused and the coupling is weak. The effect of the degree of fusion on the form birefringence of the coupler for different V-values is shown in Fig. 2. For $V = 8$, $C_x - C_y$ does not change sign as the aspect ratio varies from 1 to 1.95. This birefringence behaviour is much like that of the rectangular waveguide model in which the birefringence always exists for any aspect ratio [7]. For couplers with smaller V-values the modal fields extend more to the surrounding medium and thus resemble those of an equivalent rectangular waveguide. As the V-value is increased from 8 to 70, the form birefringence becomes similar to the Zheng results and $C_x - C_y$ occurs at an aspect ratio of 1.8. The fact that fused couplers with a dumbbell-shaped cross-section are isotopic at the degree of fusion $d/r = 1.8$ is verified again in our analysis, although it was observed experimentally that the isotropic characteristic appeared near $d/r = 1.4$ [5]. It is worth noting that when two fibres are nearly touching, i.e. when d/r is close to

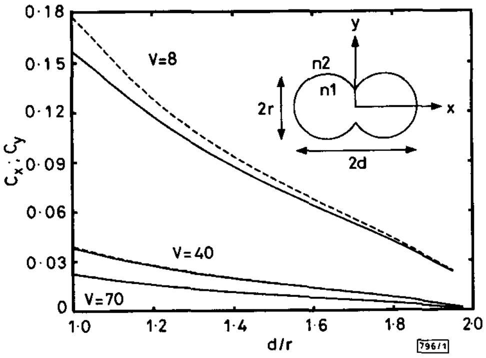

Fig. 1 *Coupling coefficients for x and y polarisation as functions of the degree of fusion d/r for V = 8, 40 and 70*

Inset: dumbbell-shaped cross-section of fused coupler

—— C_y
- - - - C_x

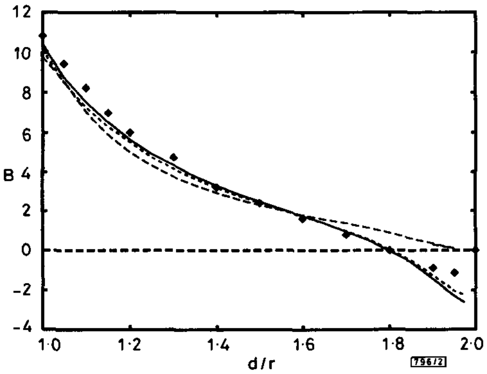

Fig. 2 *Form birefringence of fused couplers as function of degree of fusion d/r for V = 8, 40 and 70*

- - - - $V = 8$
-------- $V = 40$
—— $V = 70$
● Zheng results [8]

2.0, the polarisation birefringence is still significant for couplers with large V-values in our analysis. This behaviour is consistent with the experimental results in [5] which showed that $C_x - C_y$ was very large at large aspect ratio. However, in the Zheng results the value of $C_x - C_y$ becomes zero when d/r is close to 2.0. This discrepancy is due to the fact that under the assumption of $V \rightarrow \infty$, as in the Zheng analysis, the boundary of the fused coupler is like a metal wall and thus there would be no coupling or no interaction between the two (metal-walled) fibres that are just touching. The dependence of the aspect ratio at which $C_x = C_y$ on the V-value of the coupler is shown in Fig. 3. It is seen that the aspect ratio at which the coupler is isotropic is asymptotically close to 1.8 as the V-value increases. For couplers with smaller V-values the isotropic point occurs at weakly fused condition and is very sensitive to the variation of the V-value.

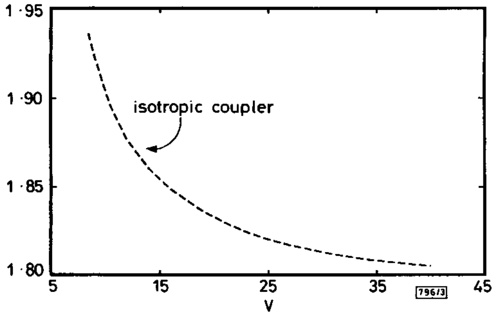

Fig. 3 *Variation of aspect ratio at which* $C_x = C_y$ *for coupler as* V *increases from 8.5 to 40:* $n_1 = 1.45$, $n_2 = 1.0$

Conclusions: The influence of the waveguide aspect ratio on the form birefringence of fused couplers with dumbbell-shaped cross-sections has been investigated rigorously based on a full-wave theoretical approach. It was found that for couplers with a small V-value (≤ 8) the birefringence does not disappear for degree of fusion from 1 to 1.95. As the V-value of the fused coupler becomes large, the aspect ratio at which the isotropic point ($C_x = C_y$) occurs is asymptotically close to 1.8 and the polarisation effect is still significant under conditions of weak fusion.

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T.-L. Wu (*Department of Electrical Engineering, National Taiwan University Taipei 106-17, Taiwan, Republic of China*)

H.-C. Chang (*Department of Electrical Engineering and Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei 106-17, Taiwan, Republic of China*)

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Selfaligning demodulator for remotely operated fibre optic magnetic sensor system

C.K. Kirkendall and F. Bucholtz

Indexing terms: Fibre optic sensors, Magnetic field measurement, Magnetostrictive devices

A technique for automatic phase alignment and phase sensitive detection for a fibre optic magnetostrictive sensor is described. The technique, which was successfully implemented in an undersea system for making long term measurements, is applicable to a variety of phase sensitive detection problems involving remote sensing.

Recently, a fibre optic magnetic sensor system for undersea applications was reported [1]. Fig. 1 shows the main components of the system where a single laser drives a system comprising a number of remote, undersea interferometric sensors. In the system shown, the output of the magnetic demodulator is trasmitted back to the sensor for closed-loop operation [2]. In typical operation, a modulation or 'dither' field is applied to the magnetostrictive element and phase sensitive detection is used on the interferometer output to demodulate the magnetic signal [3]. In the laboratory, phase sensitive detection is easily accomplished because the sensor and the detector are in close physical proximity. However, in an undersea system such as described in [1], the sensor and phase sensitive detector (PSD) may be kilometres apart. Furthermore, although manual alignment of the phase of the reference signal in the PSD is easily accomplished in the laboratory, it is time intensive and impractical in a field-operable multichannel system. The technique described here performs phase sensitive detection with a reference signal which automatically adjusts its phase to optimise the magnetometer output. An automatic phase sensitive demodulation system using the technique described here was successfully implemented in an array of eight fibre optic vector magnetometers.

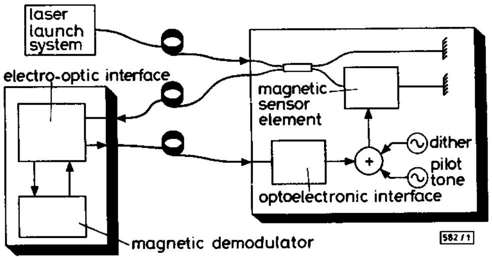

Fig. 1 *Array of remotely operated fibre optic magnetometers using single laser source*

The signal produced from a fibre optic interferometric magnetostrictive sensor element follows a square-law response [3, 4]. Applying a magnetic dither $h_d \cos\omega_d t$ to the transducer causes lower frequency magnetic signals to be upconverted around ω_d. For a total magnetic field $H = H_o + h_p \cos\omega_p t + h_d \cos\omega_d t$, where H_o is the DC magnetic field, $h_p \cos\omega_p t$ is a low frequency pilot tone, and $h_d \cos\omega_d t$ is the dither, the resulting magnetic signal upconverted around ω_d at point A in Fig. 2 is given by

$$V_A = K h_d (H_o + h_p \cos\omega_p t) \cos\omega_d t + R(t) \sin\omega_d t \quad (1)$$

The first term represents the upconverted DC and pilot tone magnetic signals around the dither where K (V/nT) is a constant comprising the scale factors of the transducer, optics, and electronics. $R(t)$ in the second term can be expanded to show the contributions