Interferometric technique for measuring dispersion of high order modes in optical fibres

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An interferometric technique for chromatic dispersion measurement of higher modes in short lengths of high order mode fibres is presented. The dispersion is measured using the wavelength dependence of the interference signal between the basic mode and the high order mode. Neither mode transformers nor RF circuitry are required.

Introduction: Present and future high capacity optical communications systems require accurate chromatic dispersion management. In particular, it is important for dispersion management modules to exhibit continuous dispersion and dispersion slope compensation across the entire transmission band. An attractive approach for achieving this goal is to utilize the large negative dispersion and dispersion slope of high order modes of specially designed high order mode (HOM) fibres. Such fibres are typically used in conjunction with mode transformers, which transform the signal from the basic mode of the transmission fibre to the specified high order mode of the HOM fibre, and back again. To produce the HOM fibres, and to assemble them into dispersion management modules with specified values of dispersion and dispersion slope, one needs to be able to measure their dispersion curves (i.e. wavelength dependence of dispersion) easily and accurately. In particular, it would be useful to be able to measure the dispersion using only a few metres length samples of the HOM fibre. An obvious method is to utilise the mode transformers in order to connect the sample to standard commercial dispersion measurement systems, typically based on expensive and complex RF circuitry. In this Letter we describe an alternative method, which is a variant of the interferometric measurement technique (see for example [6-9]). The method requires neither mode transformers nor RF circuitry, and can be easily implemented using standard laboratory equipment.

\[ P(\lambda + \delta \lambda) = A + B \cos(\phi_0 + \alpha(\lambda) \delta \lambda) \]

where

and \( \Delta \lambda \) is the absolute value of the group delay difference per unit length between the two modes. By extracting the oscillation period of \( P(\lambda + \delta \lambda) \), as a function of \( \delta \lambda \), it is possible to measure \( \alpha(\lambda) \) and hence \( \Delta \lambda \). In practice, it is only possible if \( \alpha(\lambda) \) is at least an order of magnitude larger than the resolution of the tunable laser, typically 1 pm. An additional condition is that \( \alpha(\lambda) \) as a function of \( \lambda \) changes slowly enough within a single oscillation period. For typical HOM fibres presented in this Letter, these two conditions limit the range of sample lengths \( L \) for which the method is effective to approximately 1 to 50 m. In some special cases however [9], the group delay of the LP01 mode may coincide with the group delay of the LP01 mode at some particular wavelength \( \lambda_0 \) within the measurement band. In this case \( \alpha(\lambda_0) \) becomes very large and the measurement method does not work in the immediate vicinity of \( \lambda_0 \).

Having measured \( \Delta \lambda \) as a function of wavelength \( \lambda \), it is then a simple matter to take the derivative and obtain \( \Delta \lambda(\lambda) \), which is the difference in the dispersion values of the two modes. Thus, the proposed method does not directly measure the dispersion of the high order mode, but rather the absolute value of the difference between the dispersion of the high order mode and that of the basic mode. However, the dispersion of the basic mode, primarily governed by material dispersion, is typically much smaller than that of the high order mode. Also, it is quite insensitive to the fine details of the refractive index profile design of the fibre, and can be accurately calculated from simulations. Using the calculated dispersion of the basic mode, together with knowledge of the sign of the dispersion of the high order mode, it is then possible to extract the value of the dispersion of the high order mode.

The analysis described assumes that only the basic mode and one high order mode are excited in the fibre. If other high order modes are also excited, then additional cosine terms will appear in eqn. 2, and Fourier analysis can be used to individually isolate them.

Results: We now show the results of the application of the proposed measurement method to a specific sample of HOM fibre. This sample, with a length of 4.76 m, was taken from a 70 m length of fibre the LP01 dispersion of which had been previously measured using mode transformers and a commercial chromatic dispersion analyser. As stated previously, this HOM fibre was designed to have a large negative dispersion for the LP01 mode. In Fig. 2 we show the measured power against \( \delta \lambda \) around three different wavelengths: 1525, 1545 and 1565 nm. For each wavelength
the cosine form of eqn. 2 is clearly seen. Furthermore, the strong wavelength dependence of \(\alpha(\lambda)\), and therefore \(\Delta\sigma(\lambda)\), is a direct manifestation of the high negative dispersion of the LP_{04} mode.

![Fig. 2 Measured interference signal, \(P(\lambda + \delta\lambda)\), for three different wavelengths](image)

![Fig. 3 Wavelength dependence of group delay difference, \(\Delta\gamma(\lambda)\)](image)

In Fig. 3 we plot the function \(\Delta\gamma(\lambda)\) over the entire C-band, 1525-1565 nm. The dispersion of the basic LP_{04} mode for this specific HOM fibre is \(+23\, \text{ps/(nm km)}\) at 1550 nm, with a dispersion slope of \(+0.06\, \text{ps/(nm km)}\). Using these values, and the knowledge that the dispersion of the LP_{04} mode is negative, we have calculated the dispersion curve \(D(\lambda)\) of the LP_{04} mode. The result is plotted in Fig. 4, together with the conventional dispersion measurement of the 70 m length of fibre from which the sample was taken. As can be seen, the two measurements agree to within better than 5%, in spite of the different lengths of the two fibres.

![Fig. 4 LP_{04} mode chromatic dispersion, measured using both interferometric and conventional methods](image)

**Conclusions:** We have presented a simple method for measuring the dispersion of high order modes in short samples of HOM fibres. The method does not require mode transformers or RF circuitry, and can be readily implemented using standard equipment. It constitutes yet another tool in the emerging field of high order mode technology.

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**References**


**Mach-Zehnder interferometer using single standard telecommunication optical fibre**

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It is demonstrated that a single, short-length, standard telecommunication optical fibre can function as an interferometer when subjected to hydroxyl-flooding. The interferometer is based on the mode beating effect arising from the induced-refractive index change.

**Introduction:** Sensors, filters and intermodal couplers have been demonstrated using the interference between modes in special optical fibres [1-3]. Such systems are very useful, and could be employed more widely if the requirements on the multimode fibre could be relaxed. In this Letter, a technique is described that makes it possible to construct a monolithic fibre interferometer from most singlemode silica-based fibres. The technique is based on increasing the refractive index of an optical fibre by using heat and hydrogen treatment [4,5]. A section of the available fibre is H2-loaded and heated to 1000°C for ~1s, leading to massive hydroxyl formation (referred to as OH-flooding [6,7]). This leads to a large refractive index increase, sufficient to render a single-mode fibre bimodal in the treated region. We illustrate the poten-