PICOSECOND PULSE DISPERSION IN CLADDED GLASS FIBRE

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Picosecond pulse dispersion measurements have been made on short lengths of multimode glass fibre. With a narrow input beam rapid mode conversion occurs initially, but an equilibrium is reached after ~10 m and the transmitted pulse then broadens at a linear rate of ~10 ps/m.

1. Introduction

A convenient method of determining the information-carrying capacity of an optical fibre waveguide is to measure the broadening of a transmitted optical pulse [1,2]. If conventional photodetectors are used the response time is normally limited to ~0.2 ns so that pulse dispersions in short lengths of multimode fibre, or in single-mode and Selfoc fibre, cannot easily be obtained. However, it has been shown [3] that an ultrafast optical shutter can be constructed by utilizing the birefringence induced in a dielectric liquid through the optical Kerr effect. The power required to produce a reasonable transmission through the gate is ~100 MW/cm^2 and can be provided by a mode-locked solid-state laser or the equivalent. The time for which the shutter is open is determined by the mode-locked pulse, unless it is shorter than the relaxation time of the Kerr material (which can be as small as 2 ps for carbon disulphide), so that a resolution in the picosecond regime becomes possible. Using a shutter of this kind it is possible to construct what is, in effect, an optical sampling oscilloscope or 'picoscope', having a picosecond time resolution. It can measure directly the shape of dispersed optical pulses or, more precisely, the convolution of the dispersed pulse with the shutter actuating pulse. In particular we report here measurements of pulse dispersion in short lengths of multimode cladded glass fibre.

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2. Experimental arrangement

A detailed description of the picoscope will be reported elsewhere [4] and only a brief discussion of the main components is given here. The optical source is a mode-locked ruby laser [5,6] which is simultaneously Q-switched and mode locked so as to produce a train of ~15 pulses each of typically 25 ps duration at a wavelength of 0.69 μm. A beam splitter, fig. 1, divides the pulse train into two components one of which, after a suitable variable delay, provides the actuating pulses for the optical shutter. The latter consists simply of a cell, 5 mm thick, filled with carbon disulphide and placed between crossed polarizers [3]. The variable optical delay, which determines the time of opening of the shutter relative to the pulse being sampled, comprises two fixed prisms together with a retroreflector prism mounted on a high-precision drive unit.

The probing pulses are formed from the second component of the pulse train by passing it through another cell containing a suitable liquid so that the wavelength is shifted by stimulated Raman scattering. Any remaining radiation at 0.69 μm is removed by suitable filters. A change in wavelength is essential in order to differentiate between the dispersed pulse and scattering from the actuating pulses in the shutter. After pass-

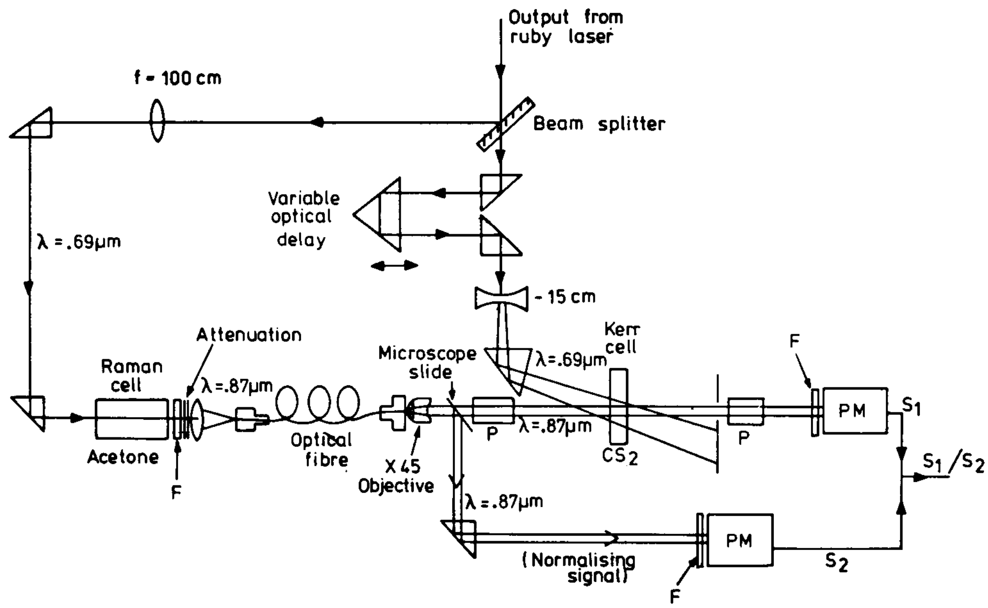

Fig. 1. Experimental arrangement for fibre dispersion measurements. F = filter (RGN 9) to block radiation at 0.69 μm. P = Glan–Thompson polarizer. PM = photomultiplier.

ing through both the material, or component, under test and the shutter the sampled signal is detected with a photomultiplier. By varying the optical delay in suitable steps the whole of the dispersed pulse can be sampled in sequence and its variation with time determined. The Y axis of the recorder is fed by the ratio of the transmitted and a normalizing signal while the X axis is driven in synchronism with the variable optical delay. The entire system is automatically driven, and the recordings processed, by a digitized control system. The laser is fired every 1.5 s and a complete intensity/time scan can be obtained in five to ten minutes depending on the sampling interval.

Acetone was used in the Raman cell as the resulting probe wavelength (0.87 μm) is very close to those of the gallium arsenide injection laser and light-emitting diode which are the sources most likely to be used in an optical fibre communication system. In addition most optical fibres of practical significance have a minimum loss in the region of this wavelength. The probe pulses were coupled into the fibre through a lens of 5 cm focal length and the fibre output was collimated into the gate with a X45 microscope objective having a numerical aperture nearly equal to that of the fibre at this wavelength. The gating pulse was spatially expanded to give an adequate acceptance angle for the probe beam. Filters (RGN 9) were used to remove 0.69 μm radiation from the probing pulses and from the photomultipliers.

3. Fibre characteristics

The fibres had a core of Schott F7 glass, diameter 55 μm, and a cladding of Chance/Pilkington ME1 glass, thickness 20 μm, and were wound loosely on black drums of 5.5 cm radius. The numerical aperture was 0.64 and the attenuation at 0.87 μm was ~320 dB/km. The lengths chosen for measurement were such that the corresponding propagation delay was (nearly) an integral multiple of the cavity round trip time (~8 ns) so that there was no need to make major changes in the optical delay, i.e. a particular probe pulse was sampled at the shutter by an actuating pulse occurring later in the mode-locked train. The fibre ends were carefully cut and supported in mounts con-

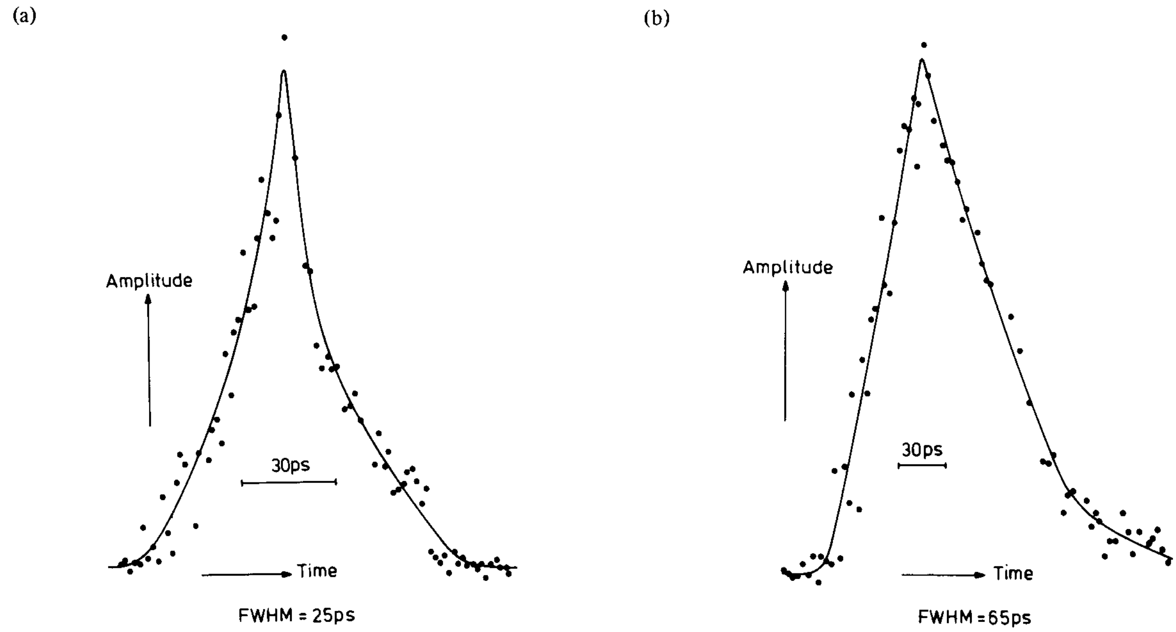

Fig. 2. Output scans obtained with fibre lengths of (a) 0 m; (b) 3.5 m.

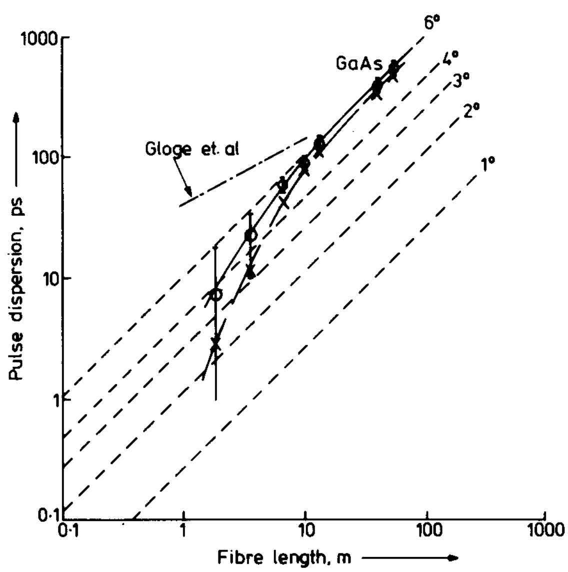

Fig. 3. Pulse dispersion as a function of fibre length obtained as follows: ○ measured; X deduced from measured angular width of output beam; --- calculated from ray propagation model assuming neither mode conversion nor mode filtering.

taining index-matching liquid. The angular width of the probe beam at the input to the fibre was measured as 0.5° at the e^{-2} X maximum intensity points.

4. Results

The response obtained without a fibre inserted in the probe path is shown in fig. 2(a) and represents the convolution of the transmission function of the gate with the probe pulse. The full width at half maximum is 25 ps and is reasonably reproducible. Typical of the scans obtained for various lengths of fibre is that in fig. 2(b) where each point is integrated over three laser shots to provide some smoothing. The pulse dispersion, defined as the increase in half-intensity width of the transmitted pulse, for the various fibre lengths is indicated by the circles in fig. 3 where the scatter in the dispersion results is indicated by the error bars. Also shown are measurements taken with a semiconductor laser, again for an input beam width of 0.5°, over lengths of 40 m and 55 m. In this case an avalanche photodiode detector and sampling oscilloscope were used. Although the wavelength at which these measurements were made (0.90 μm) was slightly different from the others (0.87 μm) the extrapolation is valid since we have confirmed in other experiments that the wavelength dependence is negligible. For example it has been found, by using different liquids in the Raman cell, that for a given input beam width and fibre the dispersion and the output beam width are the same at wavelengths of 0.69 μm, 0.78 μm and 0.87 μm.

It can be seen from fig. 3 that the measured dispersion initially rises quite rapidly, and then more steadily at longer lengths, and it is interesting to compare this behaviour with that expected in an ideal fibre.

We have therefore calculated, for an input beam with a gaussian spatial distribution, the variation of dispersion with length using the simple ray propagation model [7] which has been found to give satisfactory results for fibres under multimode conditions [8]. Thus the dotted lines in fig. 3 represent the pulse dispersion in a geometrically-perfect fibre exhibiting neither mode conversion nor mode filtering, for the indicated semi-angular widths in the core. It can be seen that the measured dispersion rises more rapidly than predicted by theory at short lengths but at the same rate at longer lengths, seeming to indicate that immediately after launching mode conversion occurs. Thereafter it decreases to a negligible amount and the dispersion then corresponds to that for a beam width in the core of 6°.

In order to check for the presence of mode conversion the angular width of the output beam was measured, with a photodiode array, for the same lengths of fibre. These results are also shown in fig. 3 by calculating the theoretical dispersion corresponding to the measured angular widths (in other words the beam widths are plotted relative to the angles shown on the dotted lines). The results from the two sets of measurements are in good agreement and show that over the first ten metres (a) the dispersion increases more rapidly than would be expected from the ray propagation model and (b) the beam expands, indicating the presence of mode conversion. At a larger distance from the launching end the dispersion increases linearly with length, the beam width remains constant, and no further mode conversion is observed, although this may reflect a balance between mode conversion and mode filtering [8].

The only other picosecond dispersion measurements are those of Gloge et al. [9] which are also shown in fig. 3 for comparison. These authors used a neodymium/glass laser operating at 1.06 μm to open the shutter and produced the probe pulses by second-harmonic generation to 0.53 μm. Lengths of 0.93 m, 2.73 m and 10.0 m were measured with an input beam width estimated to be ~7°. The fibre loss at 0.63 μm was 1800 dB/km. The slope of the curve is smaller than that given by the simple ray model indicating that the number of modes progressively decreases along the fibre, i.e. there seems to be a mode filtering effect. The numerical aperture of the fibre was small (0.22) and it was more than filled by the input beam. Thus at the shorter lengths some light reaching the detector might have travelled, at least partially, along the cladding thus giving rise to an anomalously high dispersion. A high value of cladding loss [8], or imperfections at the core/cladding interface [9], would also have exerted a preferential filtering effect on the higher-order modes, thus giving rise to the observed rapid fall in the rate of pulse dispersion. In the present measurements the input beam was much narrower than the large acceptance angle of the fibre and mode conversion due to distortion and strain is a more likely process than mode filtering.

5. Conclusions

We have used a picosecond optical sampling oscilloscope to measure the dispersion of a multimode fibre. When a narrow input beam is launched, rapid mode conversion occurs in the first few metres and an equilibrium is established after ~ 10 m. Thereafter, the pulse broadens at the rate of ~ 10 ps/m. Once equilibrium has been reached, as confirmed by measurements of the output angle, the pulse dispersion is a linear function of length, as predicted by the ray propagation model.

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