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Experimental demonstration of intermodal dispersion in a two-core optical fiber

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The recent prediction that intermodal dispersion can play a significant role in pulse evolution in a two-core optical fiber was confirmed experimentally. A picosecond pulse at 1.548 μm launched into one core of a meters-long two-core fiber was found to come out of either core of the fiber as two temporally separate pulses. By measuring the time delay between these two pulses, the intermodal dispersion in the fiber was estimated to be 1.13 ps/m, in good agreement with theory.

An optical fiber with two identical single-mode cores supports two normal modes: the even mode with a symmetric field distribution and the odd mode with an antisymmetric field distribution. It is the beating between these two modes that gives rise to the phenomenon of optical power transfer between the two cores of the fiber.[1] As the fiber supports two modes, there must exist intermodal dispersion in the fiber, which arises from the group-delay difference between the two modes.[2] It has been predicted that the intermodal dispersion in a two-core fiber has the effect of breaking up optical pulses launched into one core of the fiber, and hence, sets a limit on the speed of ultrafast switching in the fiber.[2] Calculation shows that a typical two-core fiber of several hundred coupling lengths can upset the switching of picosecond pulses.[2] In fact, intermodal dispersion should exist in all kinds of evanescent-field couplers and fused tapered couplers and could limit the bandwidths of such devices.[3] In this Letter, an experimental demonstration of the pulse-breakup effect produced by the intermodal dispersion in a two-core fiber is reported, and a comparison with the theory is made.

The experimental setup is shown in Fig.1. Transform limited soliton pulses of duration $1-1.3$ ps at the wavelength $1.548\,\mu$m were generated by a mode-locked fiber laser based on polarization switching[4] and launched into one core of a two-core fiber, which was 3.18 m long. The pulses were suitably attenuated (up to 20 dB) before launch into the fiber to ensure linear propagation. A polarization controller was also included to control the polarization state of the input light. The two-core fiber used in our experiments had a cutoff wavelength of 940 nm, a core diameter of $7.2\pm0.4\,\mu$m, a center-to-center core separation of $14.8\pm1.5\,\mu$m, and a peak index difference of 0.0045 between the cores and the cladding. The fiber was kept as straight as possible to minimize bend-induced mode coupling and loss. Light from a particular core of the fiber was selected by appropriate butting of a single-mode fiber at the end face of the two-core fiber. The output light from the two-core fiber was amplified optically and its temporal characteristics measured with a background-free autocorrelator.

The output from the autocorrelator is shown in Fig.2, which indicates clearly two temporally separate pulses with nearly identical shapes. The large central peak shown in the figure was due to the self-correlation, and the two smaller side peaks were due to the cross-correlation of the two pulses. The result agrees with the theoretical prediction that a pulse launched into one core of a two-core fiber breaks up into two identical and distinct pulses as it propagates in the fiber, when the intermodal dispersion in the fiber is larger than the pulse duration.[2] By measuring the separation between the central peak and the side peak in the autocorrelation output, the time delay between the two output pulses, i.e., the intermodal dispersion in the two-core fiber, can be determined. The autocorrelation outputs obtained by cutting back the two-core fiber to 2.58 m, 1.75 m, and 1.25 m, respectively, are also shown in Fig.2. From the time delays measured at different fiber lengths, it is confirmed that the intermodal dispersion is linearly proportional to the fiber length. A linear fit of the data yields a value of 1.13 ps/m, as shown in Fig.3. There was no significant difference in the time delay measured with light from either core of the fiber.

The intermodal dispersion in a two-core fiber is a measure of the group-delay difference between the two normal modes of the fiber and can be calculated from:[2]

$$\delta\tau = \frac{2}{c}\frac{dC}{dk}, \qquad (1)$$

where c is the speed of light in vaccuum, $k = 2\pi/\lambda$ is the free-space wavenumber with λ the wavelength, and $C = (\beta_+ - \beta_-)/2$ is the coupling coefficient with β_+ and β_- the propagation constants for the even and odd modes, respectively. To calculate the propagation constants for the two-core fiber, it is necessary to know the refractive-index profile of the fiber. The measured profile for one core of the fiber is shown in Fig.4. The profile was modelled with 17 piecewise step-index layers and analysed by a series-expansion method[5], which was developed specifically for the analysis of multi-core fibers. With the uncertainty in the measured fiber parameters taken into account, the calculated coupling length, $\pi/2C$, is 4.2 ± 1.5 mm, and the calculated intermodal dispersion is 1.82 ± 0.22 ps/m, which is larger than the experimental value 1.13 ps/m. In practice, it is impossible to make a two-core fiber with two perfectly identical cores. The discrepancy between the calculated value and the experimental value is believed to be the result of two slightly different cores. To verify this theoretically, calculations were also performed by using slightly different radii for the two cores of the fiber to model the effect due to different cores. The numerical results are presented in Fig.5, which were obtained by fixing the radius of one core and varying the radius of the other core. It is clear from Fig.5 that the intermodal dispersion in the fiber decreases with increasing core-radius difference. The measured dispersion 1.13 ps/m corresponds to a core-radius difference of only 6-7%, which is within the tolerance in the control of the core radius. The theory seems to explain the experimental result well.

Apart from intermodal dispersion, there also exists group-velocity dispersion in a two-core fiber. Group-velocity dispersion can give rise to pulse broadening instead of pulse breakup. At the wavelength 1.55 μm, a typical total dispersion parameter of 20 ps/nm/km in the fiber yields a pulse broadening of 0.08 ps/m for a 1-ps pulse, which is much smaller than the intermodal dispersion. The slight pulse broadening due to group-velocity dispersion can be seen from the autocorrelator output in Fig.2. It should be pointed out that, in the previous theoretical studies of ultrafast switching with two-core fibers (see, for example, Refs.6-9), group-velocity dispersion was considered as the only dispersion effect in the fiber and intermodal dispersion was totally ignored. Such studies could have led to unrealistic results. On the experiment side, intermodal dispersion might have already played a role in early experiments on nonlinear switching of ultrashort pulses using two-core fibers.[10]

In conclusion, we have observed the effect of pulse breakup arising from the intermodal dispersion in a two-core fiber, and hence confirmed the recent prediction made in Ref.2. The intermodal dispersion in the fiber under test was measured to be 1.13 ps/m, which agreed well with the theoretical estimation. While this effect can limit the bandwidth of the two-core fiber as a distortion-free directional coupler, it can turn the two-core fiber into a simple device to introduce a well-defined time delay between two ultrashort pulses, which could find practical application, e.g., in the control of the pulse repetition rate in a fiber laser.

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Figure Captions

Fig.1 Experimental setup for the measurement of intermodal dispersion in a two-core fiber.

Fig.2 Autocorrelator outputs for different lengths of the two-core fiber.

Fig.3 Intermodal dispersion measured as a function of fiber length.

Fig.4 Measured refractive-index profile for one core of the two-core fiber.

Fig.5 Intermodal dispersion calculated as a function of the ratio of the radii of the two fiber cores.

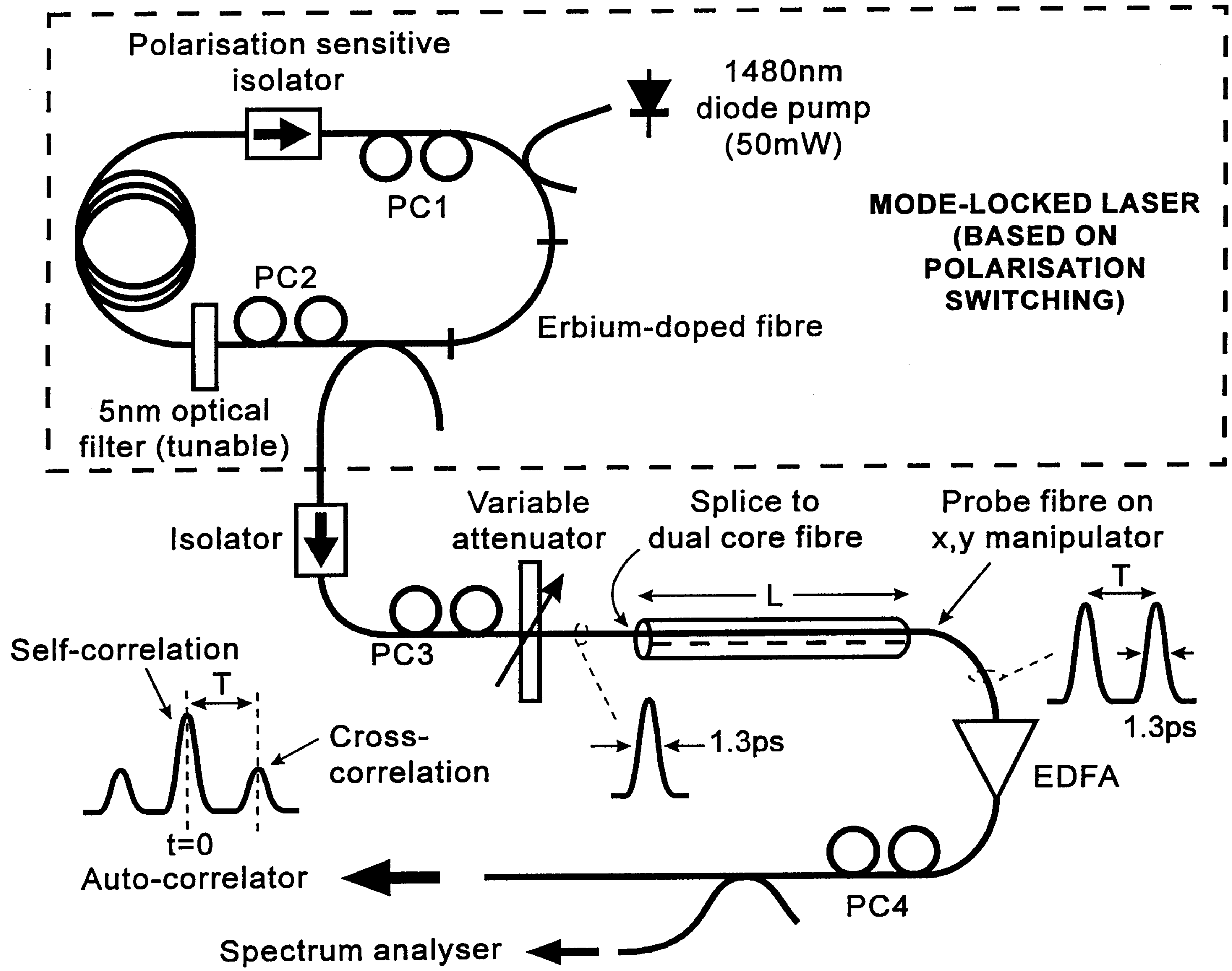

Polarisation sensitive isolator
1480nm diode pump (50mW)
PC1
PC2
MODE-LOCKED LASER (BASED ON POLARISATION SWITCHING)
Erbium-doped fibre
5nm optical filter (tunable)
Isolator
Variable attenuator
Splice to dual core fibre
Probe fibre on x,y manipulator
L
T
Self-correlation
T
PC3
Cross-correlation
1.3ps
1.3ps
EDFA
t=0
Auto-correlator
PC4
Spectrum analyser

Fig 1

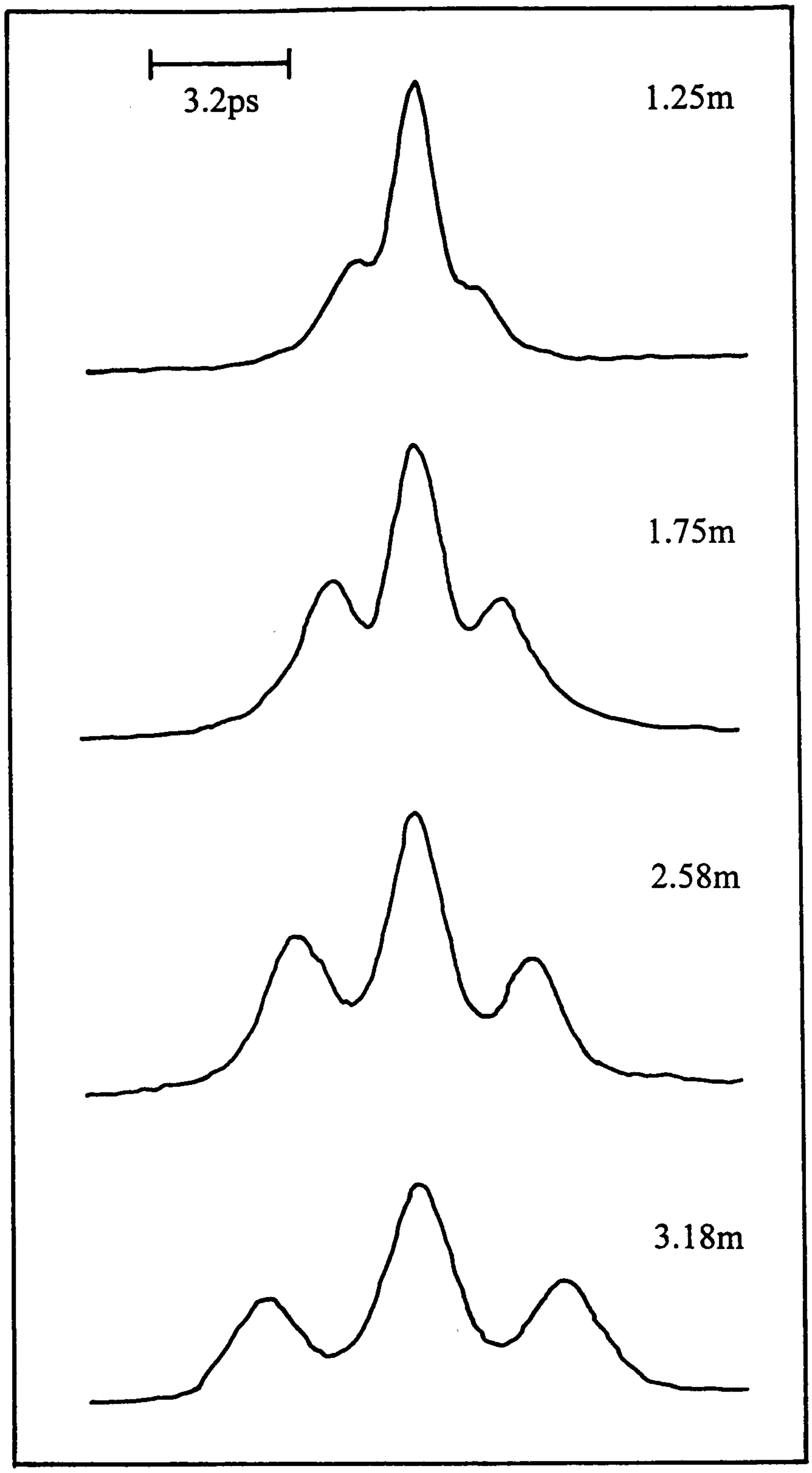


Fig.2

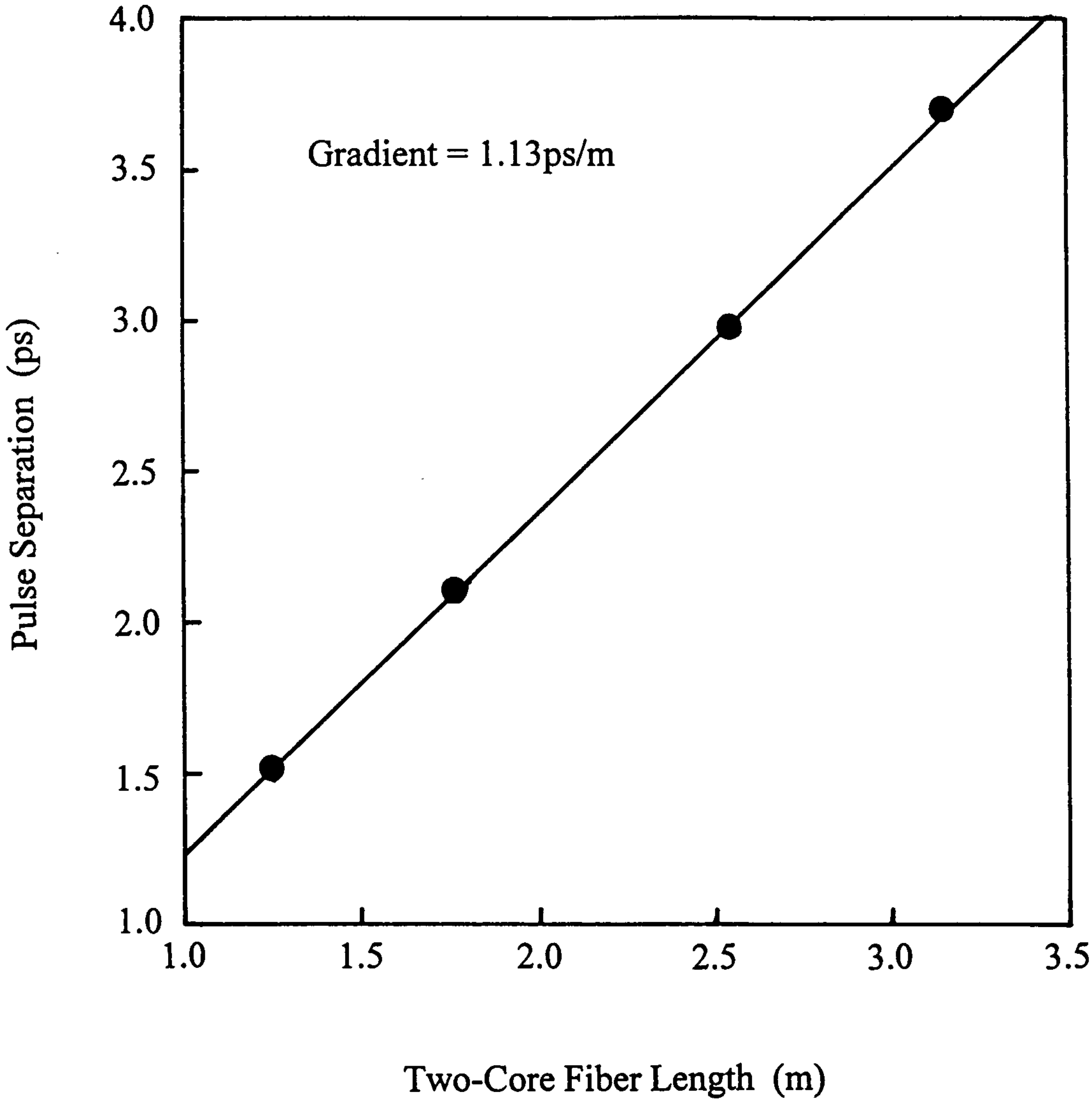
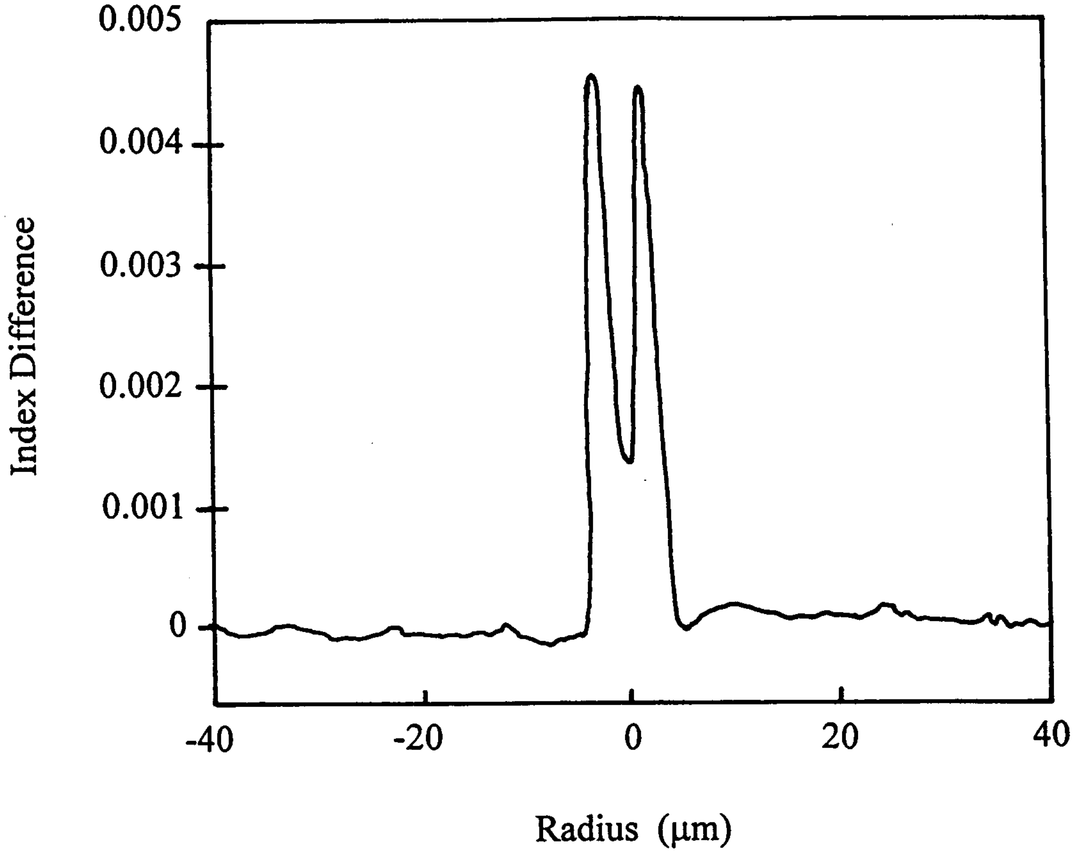

Gradient = 1.13ps/m
Pulse Separation (ps)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1.0
1.5
2.0
2.5
3.0
3.5
Two-Core Fiber Length (m)

Fig. 3



0.005
0.004
0.003
0.002
0.001
0
Index Difference
-40
-20
0
20
40
Radius (μm)

Fig. 4

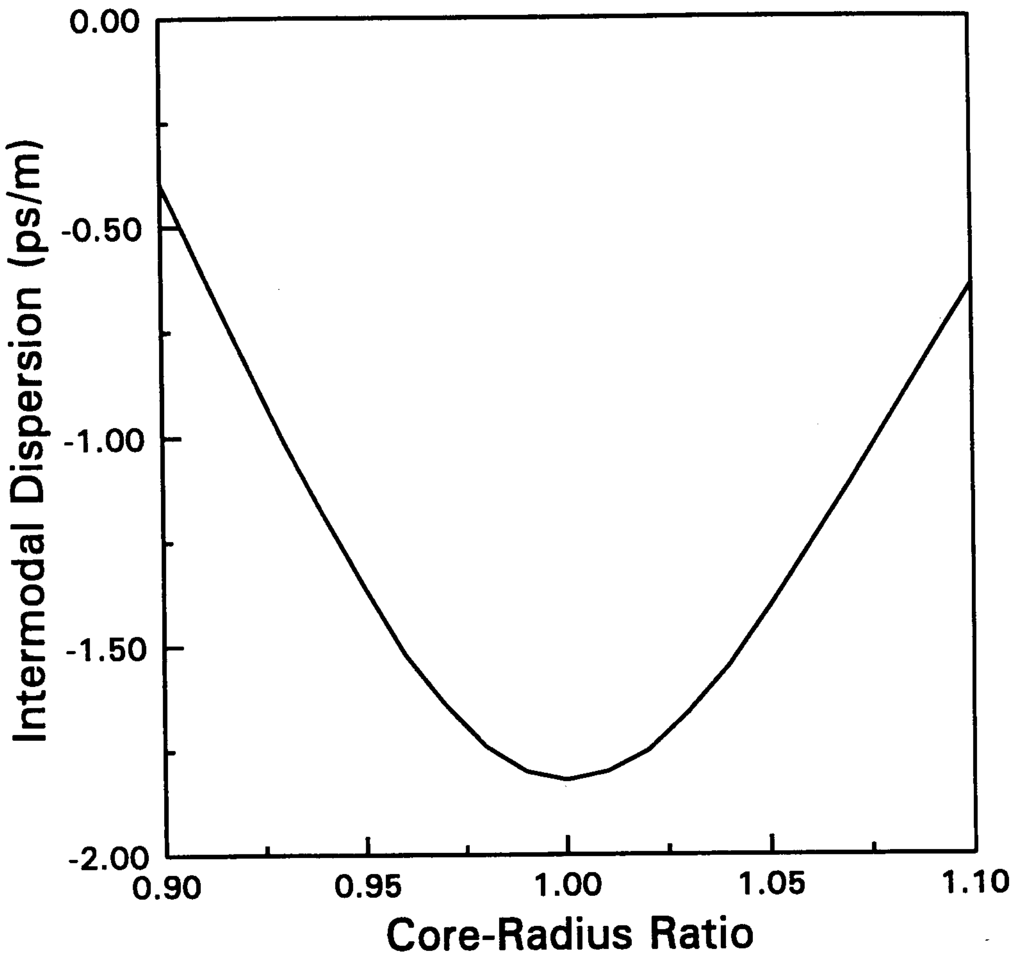

0.00
-0.50
-1.00
-1.50
-2.00
Intermodal Dispersion (ps/m)
0.90
0.95
1.00
1.05
1.10
Core-Radius Ratio

Fig. 5