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Versatile Acoustooptical Flexural Wave Modulator, Filter and Frequency Shifter in Dual-Core Fibre

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Abstract

We report the fabrication and experimental characterization of efficient flexural-wave acoustooptical modulators in velocity-mismatched dual-core dual-mode fibre. Coupling efficiencies of 100% and beyond, tunable from a few hundred kHz to several MHz, are obtainable over device lengths of 30 cm. A travelling flexural wave, excited by a silica horn, causes coupler rephasing when the acoustic wavelength equals the normal mode beat length. The device has negligible insertion loss, and through its tunability and reconfigurability has considerable potential in a variety of WDM, switching and signal-processing applications.

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A component vital to the successful implementation of single-mode fibre signal-processing and communications systems is an integrated in-line Bragg cell that can function as a modulator, SSB frequency shifter and tunable WDM tap. A number of reported devices[1,2] go some way towards achieving this goal, the most efficient to date being the flexural-wave modulator in a dual-mode single-core (DMSC) fibre developed by Kim et al[1]. In their device the LP_{11} and LP_{01} normal modes (normal modes) of the DMSC structure are coupled together by an acoustic flexural wave whose wavelength matches the intermodal beat period; launching light into the LP_{01} mode results in a frequency shifted signal in the LP_{11} mode. In practice, however, it is difficult to excite just one normal mode, and a frequency-shifted signal in the LP_{11} mode is not appropriate for efficient pigtailing to single-mode fibre. These problems are compounded by the fact that slight errors in the launching condition produce a mixture of both normal modes, resulting in an intrinsic wavelength dependence through intermodal interference. The dual-core (DC) device we have developed avoids these problems through permitting low-loss fusion splicing of single-mode fibre to either core and having negligible intrinsic coupling. This is achieved by designing the DC fibre to be phase velocity mismatched to such a degree that the normal modes of the DC coupler are almost identical to the modes of each core in isolation. Since the maximum proportion of light coupled from one core to the other is $1/\{1 + (\vartheta_i/2\kappa_i)^2\}$, where ϑ_i is the intrinsic dephasing parameter and κ_i the intrinsic coupling constant, the exchange of power between the cores will be negligible provided $|\vartheta_i/\kappa_i| \gg 1$; the normal modes of the coupler are then almost identical to the modes of each core in isolation. Provided there is sufficient overlap of the modal fields, distributed feed-forward normal mode (and hence inter-core) coupling will be achieved[5] in the presence of a flexural wave at the correct frequency. Supposing that the quasi-even and quasi-odd normal modes of the DC structure have effective refractive indices n_e and n_o, then the beat period is $L_b = \lambda/(n_e - n_o)$, and the appropriate acoustic frequency is $f_a = (n_e - n_o)c_f(f_a)/\lambda$ where c_f is the flexural wave velocity at a frequency f_a. The dispersion of flexural waves is somewhat complex[4]. At low frequencies $c_f/c_{ext} \approx \sqrt{(\pi f_a d/2c_{ext})} = \sqrt{q}$ where c_{ext} is the longitudinal wave velocity and d the fibre diameter (N.B., the analogous expression for c_f/c_{ext} in reference 5 is in error by a factor of approximately $\sqrt{2}$). This approximation overestimates c_f/c_{ext} by less than 5% for $q < 0.1$. At high frequencies c_f approaches the surface-wave velocity. In our experiments, q ranged between 0.12 and 0.37 ($d = 100\mu$m, $c_{ext} = 5760$ m/s, 500kHz $< f_a <$ 5MHz).

Stretched and unstretched portions of the same preform, milled away to a D-shaped cross-section, were sleeved and pulled into fibre. One core was arranged to be eccentric, and the other centric for ease of splicing to standard single-mode fibre. Two different DC fibres, DC1 (110 μm diameter) and DC2 (100 μm), were designed to have beat lengths of approximately 0.5 and 1 mm at $\lambda = 1\mu$m.

In setting up a modulator, a length of DC fibre was stripped of its coating, and placed in rotating clamps to permit a) elimination of any twist and b) precise alignment of the two cores in the plane containing the horn axis. An index-matching cell and a microscope facilitated this. The fibre was then bonded to a silica horn itself mounted on piezo element designed to be resonant in the desired frequency range. A matching network permitted efficient conversion of electrical into acoustic energy (see set-up in Figure 1).

Preliminary experiments were carried out to characterize c_f/c_{ext} as a function of frequency. A simple Fabry-Perot interferometer, formed between the side of the vibrating fibre and the cleaved end of a single-mode sensing fibre, was developed to measure accurately the vibrating amplitude both of the flexural wave and the acoustic horn. 780 nm light was delivered to the sensing fibre via a 3dB fused tapered coupler, and the reflected signal detected at a Si photodiode. For calibration purposes, the FP cavity spacing was dithered at 50 Hz through several reflection maxima. The wavelength of the travelling flexural wave was measured using lock-in techniques while translating the sensing fibre axially along the vibrating fibre; no acoustic damping could be measured over the 30 cm lengths used. The results of averaging over 10 or 20 acoustic periods are plotted in Figure 2 as frequency versus inverse wavelength. The gain in acoustic amplitude at the horn was found to be of the order of 10×, and the ~~frequency spectrum~~ spectral response of the horn end was found to be fairly flat, with only a few nodes.

A spectrometer/lamp combination was used to deliver tunable narrow band (1-2 nm) light to a single-core fibre spliced to the central core of the DC fibre modulator. An acoustic frequency was selected, and the optical wavelength scanned until coupling was obtained. The acoustic driving signal was amplitude modulated to permit easy detection of coupling to the second core. Once coupling had been achieved, the FP sensor was used to measure the beat length; this technique enabled L_b to be plotted as a function of wavelength for the two fibres, DC1 and DC2. The results are displayed in Figure 3. L_b is a fairly linear function of wavelength in both cases, indicating negligible dispersion of $(n_e - n_o)$ in the measured wavelength range.

Two different phenomena contribute to the acousto-optical coupling constant; the first is microbending and the second strain-optical effects. In both cases the perturbation has an anti-symmetrical transverse profile across the fibre cross-section. Anti-symmetry is essential, since the coupling constant is proportional to the integral over the fibre cross-section of the transverse perturbation profile multiplied by the product of the two optical normal mode amplitude profiles. If the perturbation were constant (as in the case of an axial longitudinal wave), the coupling constant would be zero due to normal mode orthogonality. It is therefore of considerable interest to know how the coupling strength varies with flexural wave amplitude. Using the set-up in Figure 1, we were able to measure this directly, providing data that may be related to the theory in order to clarify the relative importance of micro-bending and strain-optical effects. The horn was bonded to a length of fibre DC2 at a point $L_1 = 91$ mm from one end and $L_2 = 290$ mm from the other. It is straightforward to show that the conversion efficiency to the second core (measured at a square-law detector) will obey the relationship:

$$\eta = \sin^2 \kappa L_1 + \sin^2 \kappa L_2 - 2 \sin^2 \kappa L_1 \sin^2 \kappa L_2 \quad (1)$$

where κ is the coupling constant. A plot of κ as a function of flexural wave amplitude, obtained by solving this equation for κ using the experimentally determined values for η at different acoustic power levels, is given in Figure 4.

The intrinsic coupling in DC1 was too small to measure with our set-up, and 8.5% acousto-optical coupling was obtained at 4.6 MHz and 962.5 nm. DC2's intrinsic coupling was around 3%, and 100% (and beyond) acousto-optical coupling was achieved at 560 kHz and 1.064 μm; a heterodyne experiment investigating the degree of carrier wave suppression possible at 100% coupling has already been reported[6]. The function describing the coupling efficiency between the normal modes (approximately equal to the inter-core coupling for large degrees of intrinsic dephasing) as a function of optical wavelength λ is:

$$I_c(\lambda) = (\kappa L)^2 \operatorname{sinc}^2(L\sqrt{\{\kappa^2 + (\vartheta/2)^2\}}) \tag{2}$$

where $\vartheta(\lambda) = 2\pi(1 - \lambda_0/\lambda)/L_b$ is the dephasing parameter and L the coupler length. For L =240 mm, DC1 yielded 8.5% conversion efficiency at $f_a = 4.634$ MHz and $\lambda_0 = 962.5$ nm, corresponding to a beat length of 0.407 mm and coupling constant $\kappa = 1.2\ \mathrm{m}^{-1}$. The measured conversion efficiency with wavelength had a FWHM of about 1.5±0.5 nm (resolution limited by monochromator); this agrees well with the theoretical prediction (calculated from Eq(2)) of 1.3 nm. The excellent agreement confirms that the beat length is uniform over the full coupler length. In the case of DC2, for 25% efficiency over a coupler length of 290 mm at $L_b = 1.21$ mm, $f_a = 589$ kHz and $\lambda_0 = 1020$ nm, the theoretical FWHM width is 4nm.

In conclusion, highly dephased dual core fibre couplers are a versatile vehicle for in-line flexural-wave modulators. With appropriate design it is possible to realise 100% efficient frequency shifters over the range 0.5 to perhaps 20 MHz. Finally, it is interesting to note that, because the imposed coupling is periodically distributed in a highly controlled manner, the coupler is well behaved - unlike the chaotic behaviour seen in weakly interacting DC devices of comparable coupling lengths but uniformly distributed coupling.

References

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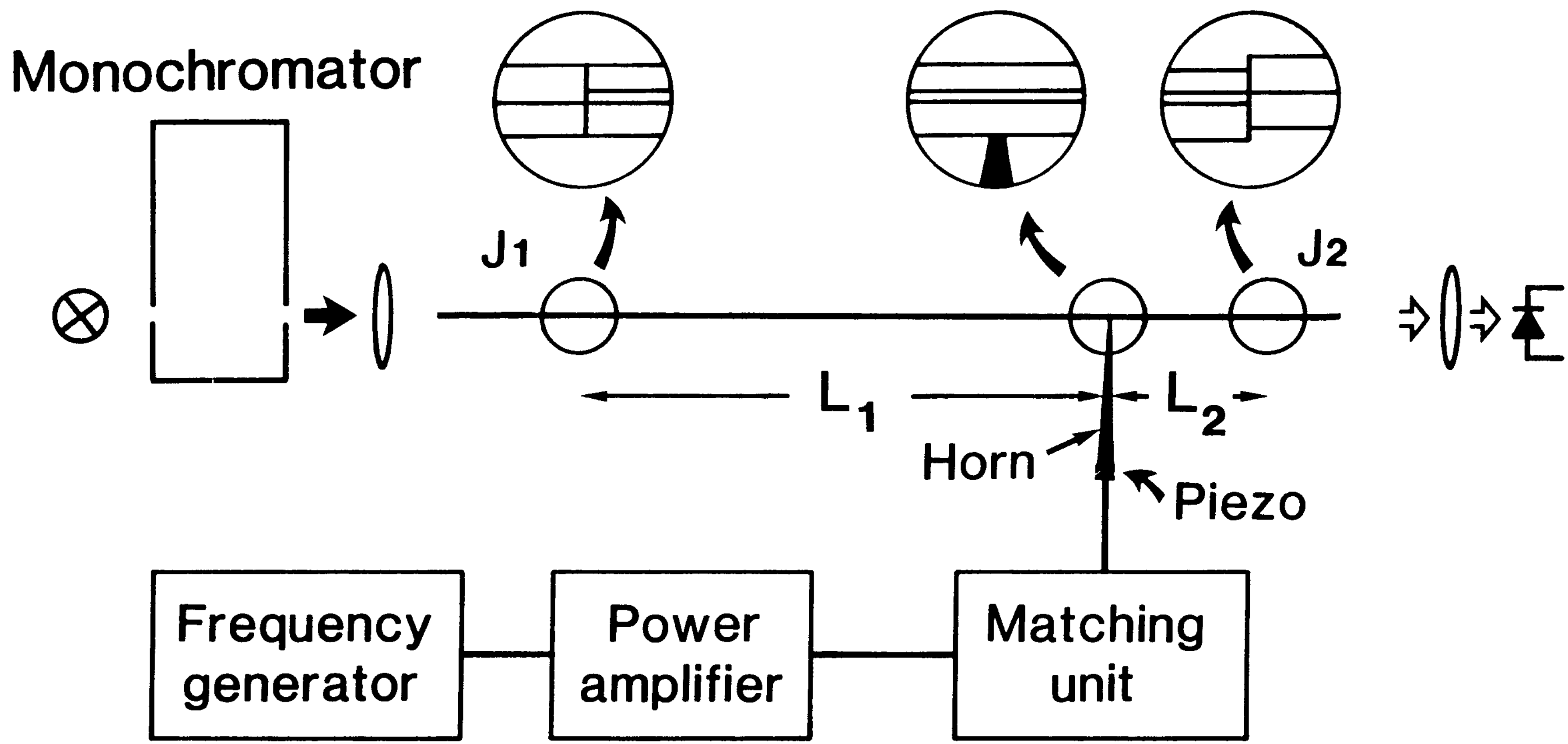
Figure Captions

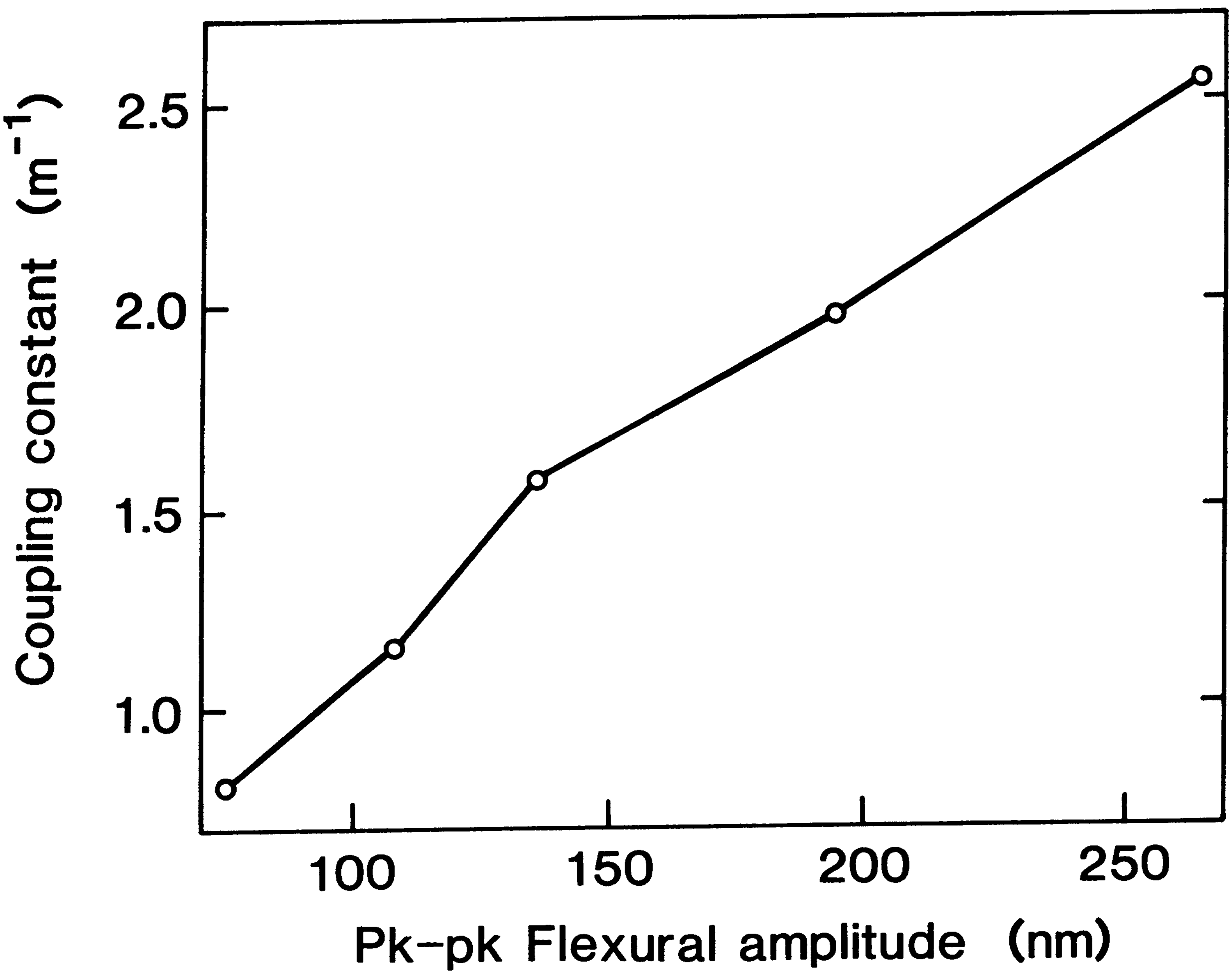
1. Experimental set-up.

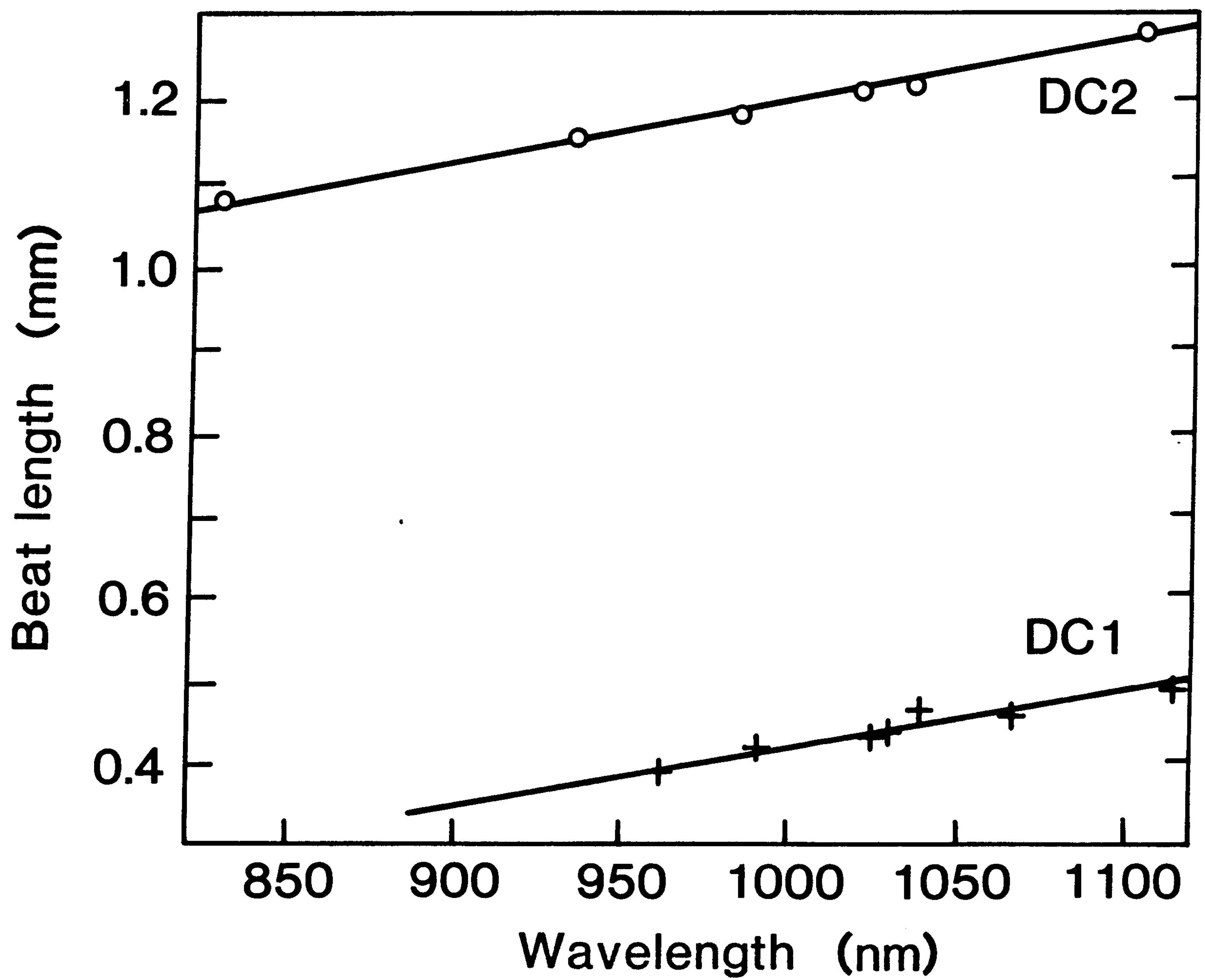
2. Experimentally determined relationship between the acoustic frequency and inverse wavelength. The high frequency group of points were measured using fibre DC1, and the low frequency group using DC2. The full curve is based on the low-frequency approximation $c_f/c_{ext} \approx \sqrt{(\pi f_a d/2c_{ext})}$ with $d = 100$ μm and $c_{ext} = 5760$ m/s.

3. Experimentally determined beat lengths for DC1 and DC2 as functions of optical wavelength. The slopes are 0.78 μm/nm and 0.55 μm/nm respectively, implying index differences of 1.28×10^{-3} and 1.82×10^{-3}.

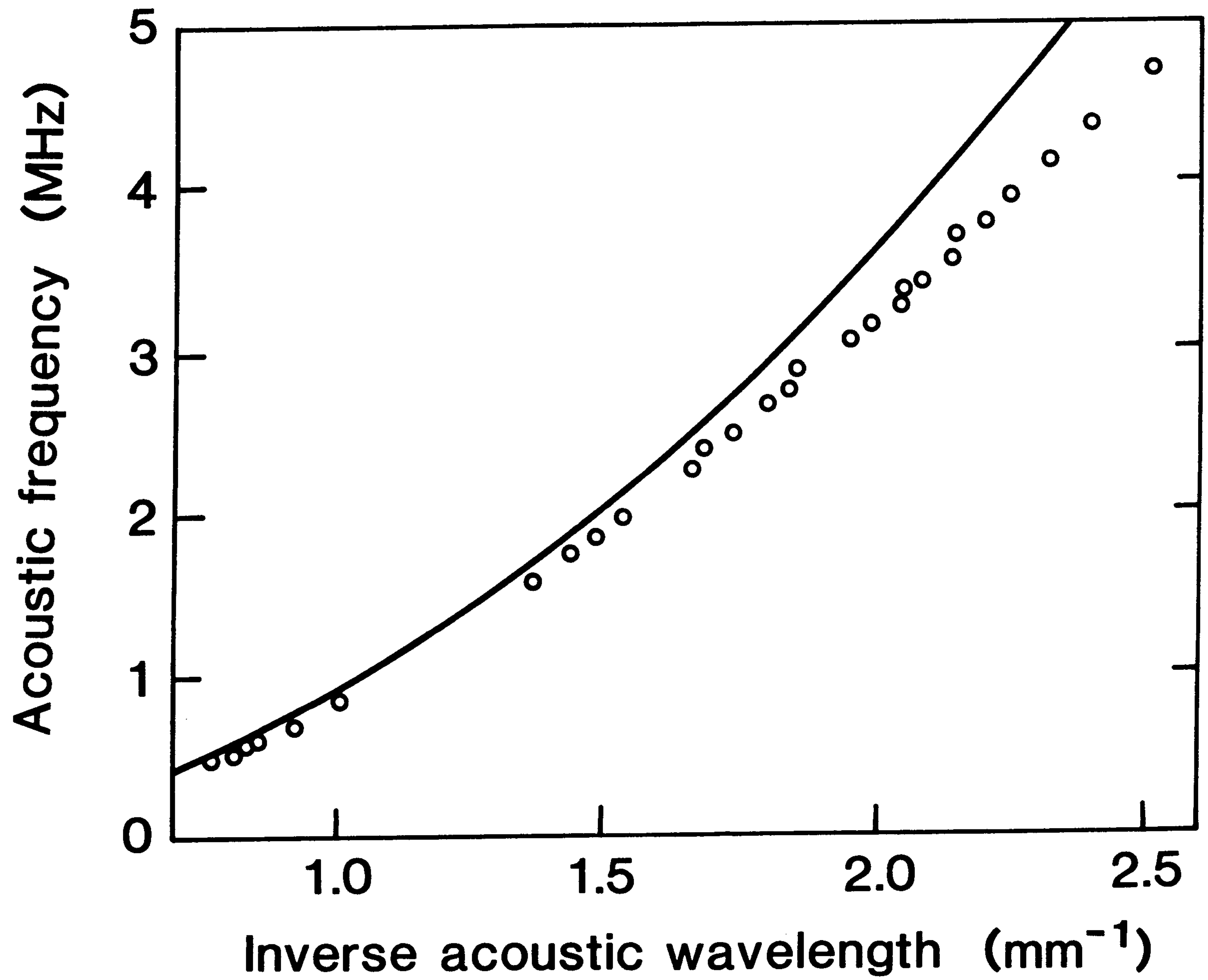
4. Coupling constant κ versus flexural wave amplitude for DC2 running at 589 kHz and an optical wavelength of 1020 nm.


Monochromator
J1
J2
L1
L2
Horn
Piezo
Frequency generator
Power amplifier
Matching unit


Coupling constant (m-1)
2.5
2.0
1.5
1.0
100
150
200
250
Pk-pk Flexural amplitude (nm)



Beat length (mm)
1.2
1.0
0.8
0.6
0.4
DC2
DC1
850
900
950
1000
1050
1100
Wavelength (nm)


Acoustic frequency (MHz)
0
1
2
3
4
5
1.0
1.5
2.0
2.5
Inverse acoustic wavelength (mm⁻¹)