Highly-efficient broadband acoustic transducer for all-fibre acousto-optic devices

S.S. Lee, H.S. Kim, I.K. Hwang and S.H. Yun

An acoustic transducer for excitation of acoustic waves to an optical fibre with high efficiency and smooth frequency response is demonstrated. Reducing the size of the transducer to an order of the acoustic wavelength has resulted in low power consumption and smaller efficiency variations during wavelength tuning.

Introduction: An acousto-optic tunable filter (AOTF) based on a singlemode optical fibre has received considerable interest for its application to dynamic gain equalisation in telecommunication systems with an advantage of ultra-low insertion loss (<0.1 dB) [1, 2]. A typical AOTF has required electrical drive power up to a few hundreds of milliwatts to produce notch depths of several dB. Such power consumption is several times higher than the theoretical limit mainly because of the relatively poor efficiency of acoustic transducers [3]. Improving the transducer efficiency is highly desirable to make the device more practical, in particular for dynamic gain equalisation which requires a relatively large number of AOTFs used in series to generate complex attenuation spectra given by optical amplifiers [2]. Previous acoustic transducers have exhibited significant frequency dependence in power consumption due to acoustic resonance inside the transducers [4], making notch depths very sensitive to optical wavelength tuning and temperature variations. In this Letter, we demonstrate an acoustic transducer with significant improvement in efficiency and frequency response.

Principle of design: Fig. 1 shows the configuration of the AOTF. The coaxial acoustic transducer comprises of a shear-mode PZT disk and a machined aluminium horn. The transducer has a central hole to which an optical fibre with a stripped section in the middle is threaded and bonded using an adhesive [5]. The tapered horn has a decreasing diameter from its base to a sharp tip and therefore acts as an acoustic amplitude amplifier. The acoustic wave, as it propagates along the optical fibre, creates periodic refractive-index modulation and geometrical deformation to facilitate mode coupling between the optical core mode (LP_{01}) and a second-order cladding mode (LP_{12}). Owing to optical modal dispersion and phase matching conditions, the coupling strength is a function of the optical wavelength. Therefore, the device acts as a spectral notch filter [1]. The centre wavelength and depth of the spectral notch are controlled by the frequency and voltage of the RF electrical signal applied to the PZT.

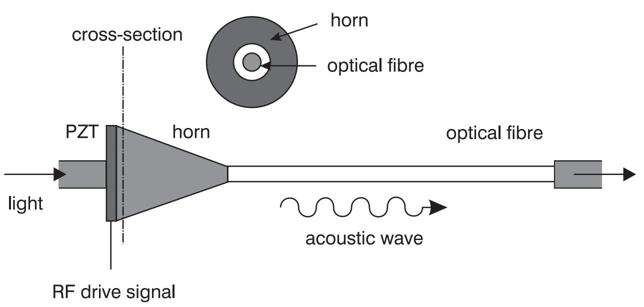

Fig. 1 *Schematic of fibre-based acousto-optic filter with coaxial acoustic transducer*

Conventional acoustic transducers had outer diameters of the PZT and the base of the horn greater than several millimetres. A large diameter ratio of the horn base to the optical fibre was used with the expectation of strong acoustic amplification along the length of the horn, leading to low drive voltages. However, it has been recognised that, due to the outer diameter being substantially greater than the acoustic wavelength (1–1.5 mm in aluminium), a large number of acoustic modes could be excited in the transducer. These higher-order acoustic modes cause poor power efficiency and strong frequency dependence through complex processes such as modal cutoffs, absorption by adhesives, resonance inside the horn, and coupling to the fundamental flexural mode. It is expected, therefore, that these problems may be largely eliminated by reducing the size of the transducer to an order of the acoustic wavelength.

Experimental results: Two acousto-optic filters, AOTF1 and AOTF2, were fabricated for comparison with two transducers of different outer diameters (*OD*) and horn lengths (*L*); For AOTF1, $OD = 5$ mm and $L = 10$ mm, and for AOTF2, $OD = 2$ mm and $L = 4$ mm. The PZT disk (resonance: 2 MHz) was attached flush with the horn. The acousto-optic interaction length in the fibre was 12 cm for both devices providing spectral notches of 4 nm width at 1550 nm. Acoustics theory [3] predicted that less than three acoustic modes would be excited in the small transducer, AOTF2 ($OD = 2$ mm), while the large transducer, AOTF1 ($OD = 5$ mm) can support more than seven acoustic modes at 2 MHz. Moreover, the analysis predicted that the fundamental acoustic mode is excited dominantly in the small transducer while the large transducer excites many higher-order modes with significant efficiency. Reducing the *OD* to less than 2 mm was prohibited by the difficulty in machining the horn and PZT.

In experiments, a function generator (output impedance: 50 Ω) and RF power meter were used to supply and measure the electrical drive power. Optical characterisation of the devices was performed using a broadband light emitting diode and an optical spectrum analyser. No electrical impedance matching was attempted between the function generator and the PZT. Fig. 2 shows the power consumption measured at each centre wavelength of the notch in the range of 1500–1620 nm when the RF voltage was adjusted to maintain a 5 dB notch depth. For this measurement, the RF frequency was varied from 2.3–1.7 MHz (tuning slope: −0.2 nm/kHz). It is clearly seen that not only the average power consumption is lower in AOTF2, but also the power variation over the optical wavelength (or RF frequency) is considerably smaller. The average power consumption in the C-band (1530–1560 nm) was only 60 mW. This value is comparable to the theoretical limit of 26 mW corresponding to both the theoretical and measured acoustic amplitude of 55 nm in the optical fibre. The maximum slope of the drive power variation with respect to optical wavelength (mW/nm) is reduced by an order of magnitude in the small transducer. The smooth frequency response is highly desirable for accurate calibration of the filter in open-loop operation and also for reduction of notch depth error against possible long-term ageing of the transducer.

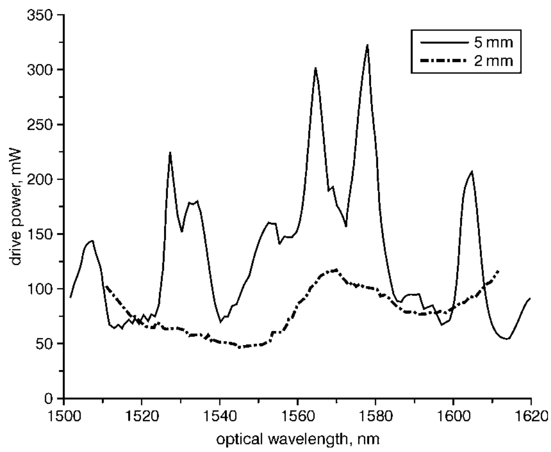

Fig. 2 *Electrical power consumption of two devices with different transducer diameters*

Desirable characteristics of the small transducer were also confirmed in direct measurement of the vibration amplitude along the horn surface using an optical vibrometer. Fig. 3*a* and *b* show normalised acoustic amplitude profiles along the surfaces of the two horns, respectively, measured at an acoustic frequency of 2.31 MHz. The increasing amplitude toward the horn tip represents the amplification effect of the horn. The sinusoidal modulation of the amplitude near the horn tip is attributed to acoustic standing waves due to a nonzero acoustic reflection from the horn tip. It is notable in Fig. 3*b* that the amplification of the acoustic wave is not clearly seen until it reaches to within ~2 mm from the horn tip. This observation reflects that the large horn suffers from significant energy loss due to excitation of higher-order modes which become cut off at about 1.1 mm away from the horn tip.

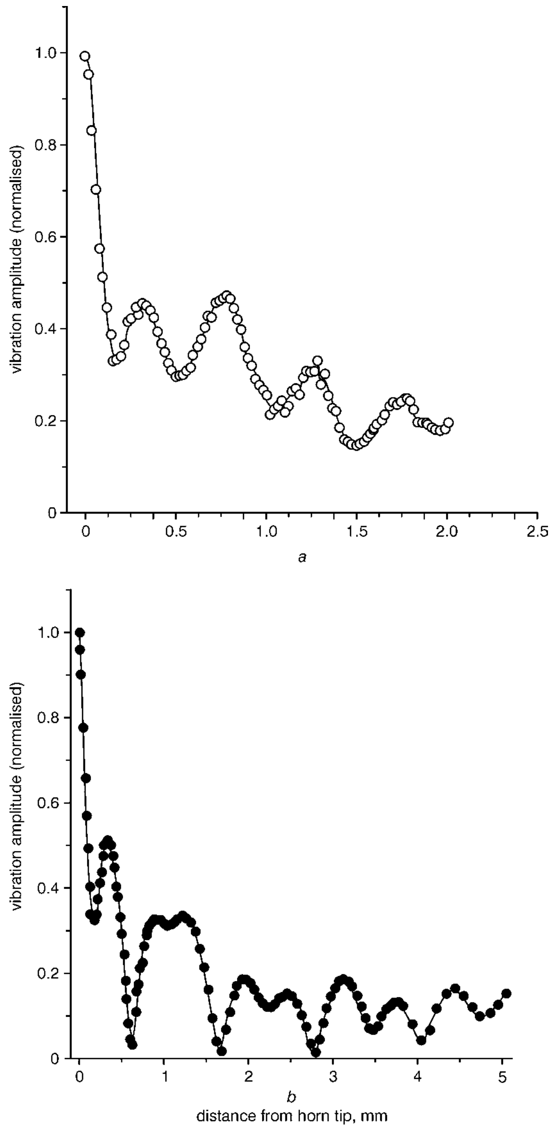

Fig. 3 *Acoustic amplitude along surface of horn for different transducer diameters*

a Diameter = 2 mm *b* Diameter = 5 mm

Conclusion: We have achieved significant improvement in the power consumption and frequency response in an acousto-optic device by using an acoustic transducer which size is reduced to that comparable to the acoustic wavelength.

Acknowledgments: The authors are most grateful to H. Engan, Young-Rak Choi, Hee-Yeal Rhy, and Kwan-Il Lee for fruitful discussions and help in fabrication of the horns. Support from Byoung Yoon Kim and W. Sorin is also appreciated.

13 June 2003

Electronics Letters Online No: 20030875

DOI: 10.1049/el:20030875

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