

# Ultrasonic splicing of polymer optical fibres

Y. Mizuno, S. Ohara, N. Hayashi and K. Nakamura

A new method of splicing polymer optical fibres by irradiation of megahertz ultrasonic waves is demonstrated. The lowest connection loss of 1.5 dB is obtained at 2 MHz, and a high mechanical strength of 59 N (close to the strength of the base polymer) is achieved at 1 MHz. It is shown that the loss and strength are in a trade-off relationship, and that the duration of ultrasonic irradiation has a certain optimal value of  $\sim 1$  s.

**Introduction:** Polymer optical fibres (POFs) have many advantages such as extremely high flexibility, low-cost installation and high safety [1, 2]. Therefore, although their loss is higher than that of standard silica glass fibres, POFs have been used both in medium-range communication applications such as home networks and automobiles [3] and in high-strain monitoring applications including Brillouin-based distributed strain/temperature sensing [4, 5]. One of the most important requirements for furthering these studies is a POF splicing technique. POF splicing based on thermal fusion has already been demonstrated [6, 7]. However, this method requires a large apparatus for moving the heat source away from the POF as well as accurate core alignment of the POFs. As no other POF splicing techniques (such as an arc-fusion splicer for glass fibres) have been reported, they need to be connected using proper adapters (e.g. SC, LC), which results in inconvenient on-site handling as well as insufficient mechanical strength for some applications where a large strain is applied. However, ultrasonic welding is known as a technique for fusing and connecting polymer materials [8, 9]. With this technique, rapid well-sealed connections can be achieved without any consumable tools (including glue and solvent) because of the high repeated stress of the ultrasonic waves. Although a POF coupler has been fabricated using ultrasonic irradiation at low frequency (40 kHz) [10], POF splicing has not been reported; high-frequency (megahertz-range) ultrasonic waves with a small oscillation amplitude [11, 12] should be used for accurate splicing of POFs with small core and outer diameters.

In this Letter, we demonstrate for the first time the splicing of POFs using ultrasonic irradiation at several megahertz. Even without polishing the fibre ends, we successfully spliced POFs with a low connection loss without using any consumable tools. The lowest connection loss of 1.5 dB is obtained at 2 MHz. A high mechanical strength of 59 N, which is comparable to the strength of the base polymer material, is also achieved at 1 MHz. In addition, we show that the connection loss and mechanical strength are in a trade-off relationship, and that the duration of ultrasonic irradiation should be  $\sim 1$  s to minimise the connection loss.

**Experiments:** The experimental setup for ultrasonic splicing of POFs is schematically shown in Fig. 1. A concave transducer (C203; Fuji Ceramics Co.; 30 mm diameter; 60 mm curvature radius) was placed on a stage at the bottom of a cylindrical acrylic container filled with degassed water. The top surface of the container was covered with an 8  $\mu\text{m}$ -thick polyvinylidene chloride (PVDC) film. The height of the transducer ( $\sim 60$  mm) was adjusted so that the ultrasonic waves were focused immediately above the film. Step-index POFs composed of poly(methyl methacrylate) (PMMA) (Super Eska; Mitsubishi Rayon Co.; 980  $\mu\text{m}$  core diameter; 1000  $\mu\text{m}$  cladding diameter; 190 dB/km propagation loss at 650 nm; 70°C heatproof temperature) were butt-coupled at the ultrasonic focal point. A silicone rubber sleeve (5 mm height; 5 mm depth; and 10 mm length) with a hole diameter of 500  $\mu\text{m}$  was used to align the POFs, and the compressive preload was kept at  $\sim 0.5$  N in this experiment. Note that the acoustic impedances of water, PVDC, PMMA and silicone rubber are  $\sim 1.5 \times 10^6$ ,  $3.2 \times 10^6$ ,  $3.4 \times 10^6$  and  $1.1 \times 10^6$  Ns/m<sup>3</sup>, respectively [13]; they are so close to one another (note that the acoustic impedance of air is  $4.1 \times 10^2$  Ns/m<sup>3</sup> [13]) that the ultrasonic waves can be propagated through each boundary of the water/film/sleeve/POF structure with low reflection. A laser diode with a 1 mW output power at 641 nm (red) was used to evaluate the connection loss at the spliced part. The exact amount of the loss was measured using an optical powermeter attached to the other end of the spliced POF. To investigate the temporal response of the loss, the powermeter was replaced by a photodiode (200 kHz bandwidth), the electrical output of which was monitored using an oscilloscope.

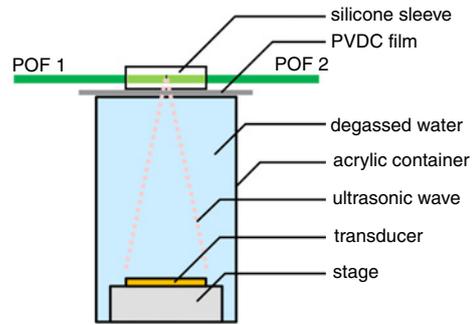


Fig. 1 Schematic of experimental setup

Figs. 2a and b show photographs of the butt-coupled part of the POFs in the sleeve before and after 1 MHz ultrasonic irradiation, respectively. The ends of the POFs to be connected were left unpolished. Before ultrasonic splicing, scattered red light was clearly observed. In contrast, after ultrasonic irradiation, the scattered light was no longer observed, which indicates that ultrasonic splicing can reduce the connection loss. Fig. 2c shows a microscopic image of the spliced POFs.

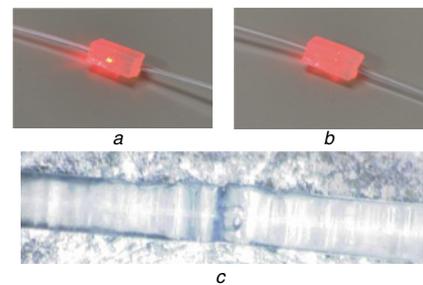
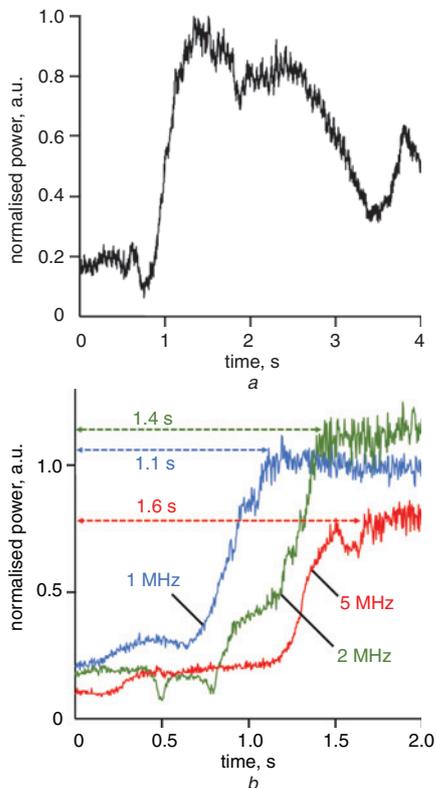


Fig. 2 Butt-coupled region of POFs

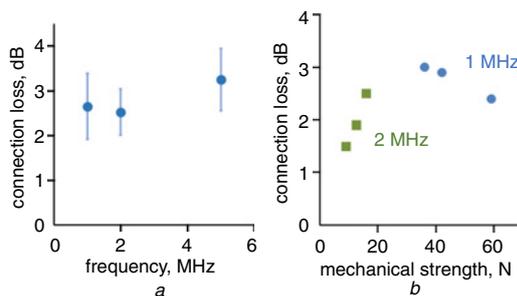
- a Photograph before ultrasonic irradiation
- b Photograph after ultrasonic irradiation
- c Microscopic image of ultrasonically spliced POFs

Fig. 3a shows the temporal response of the transmitted light power after 1 MHz ultrasonic irradiation at  $t=0$ . The transmitted power started to increase dramatically at  $t \sim 0.8$  s and reached its maximum at  $t \sim 1.2$  s. Then the power decreased irregularly. This result implies that the duration of ultrasonic irradiation has a certain optimal value, which in this case is  $\sim 1.2$  s, after which it should be stopped. The temporal responses of the transmitted light power for 1, 2 and 5 MHz ultrasonic irradiation are shown in Fig. 3b. The ultrasonic irradiation was started at  $t=0$  and stopped at the optimal timing (1 MHz, 1.2 s; 2 MHz, 1.4 s; and 5 MHz, 1.6 s). After the irradiation was stopped, the transmitted power was kept almost constant. The highest transmitted power was obtained when the ultrasonic frequency was 2 MHz.

The measured connection loss was plotted against the ultrasonic frequency, as shown in Fig. 4a. The averages of 10 values were used, and the error bars represent the standard deviation. The obtained averaged losses for 1, 2 and 5 MHz ultrasonic irradiation were comparable to that of manual coupling using a V-shaped groove ( $\sim 2.9$  dB). The lowest loss achieved among all the samples was 1.5 dB at 2 MHz, as predicted in the temporal response measurement. The mechanical strength of the ultrasonically spliced parts was measured using a tension tester (AG500N; Shimadzu Co.), as shown in Fig. 4b. The tension rate was fixed at 100 mm/min. Three typical samples spliced at each frequency were used, but the samples spliced at 5 MHz were so fragile that their data were not plotted. One sample spliced at 1 MHz had the highest mechanical strength of 59 N, which is extremely high considering that the intrinsic strength of PMMA is 70 N. The connection loss and mechanical strength seem to be in a trade-off relationship, the details of which need to be further studied.



**Fig. 3** Temporal responses of transmitted light power  
*a* Continuous ultrasonic irradiation at 1 MHz  
*b* Irradiation at 1, 2 and 5 MHz for 1.2, 1.4 and 1.6 s, respectively



**Fig. 4** Measured connection loss  
*a* Against ultrasonic frequency  
*b* Against mechanical strength for ultrasonic frequency of 1 and 2 MHz

**Conclusion:** The splicing of POFs using megahertz ultrasonic irradiation has been demonstrated for the first time. Even though the POF ends were unpolished, the POFs were successfully spliced with a low connection loss with no use of consumable tools. The averaged losses obtained after 1, 2 and 5 MHz ultrasonic irradiation were comparable to that of manual coupling aligned with a V-shaped groove. The lowest connection loss of 1.5 dB was obtained at 2 MHz, whereas a mechanical strength as high as 59 N was achieved at 1 MHz. We also showed that the connection loss and mechanical strength are in a trade-off relationship, and that the duration of ultrasonic irradiation should be

set to  $\sim 1$  s to minimise the loss. We believe that this technique will remarkably improve the convenience of POF-to-POF connection in developing future POF-based devices and systems, including highly flexible Brillouin sensors.

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One or more of the Figures in this Letter are available in colour online.

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