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Long Free-Standing Polymer Waveguides Fabricated Between Single-Mode Optical Fiber Cores

Pshko A. Mohammed and William J. Wadsworth

Abstract—Polymer waveguides with different lengths have been fabricated between two single mode fibers by using a new approach of self-writing using single photon polymerization via a xenon lamp instead of a monochromatic laser source. A photopolymerizable liquid drop deposited between two aligned fibers forms a polymer bridge between the cores of the two fibers when irradiated by light from one of the fibers. Polymer waveguides bridges 40 to 600 μm long have been fabricated between two optical fibers with single mode transmission loss 0.5 to 1.26 dB over a broad wavelength range.

Index Terms—Optical fibre, photopolymerization, polymer waveguide, self-focusing and self-writing, splicing.

I. INTRODUCTION

OPTICAL fibers are an enabling technology in many applications including routing light from remote sources to remote sensors and detectors, bringing light inside the body in diagnostic endoscopes and giving a light path immune to outside interference and misalignment. However the small core of an optical fiber presents challenges at interfaces; bringing light from a source into the fiber, building a sensor where the light must interact with its environment so cannot remain buried in the core of a fiber, bringing light from a fiber core to a detector, or joining similar or dissimilar fibers. Many different solutions are available to these challenges, one of which is to use photopolymers to produce self-aligned structures on the core of a fiber [1]–[3]. In photopolymerization, modification of the initial monomer is restricted to illuminated part of the photopolymerizable system whilst the unexposed part remains unchanged and can be removed by a solvent [4]. This means that by shining light down a fiber core into a photopolymerizable material, the polymerization is automatically aligned with the fiber core, greatly simplifying the alignment process. Furthermore, polymerization of the monomer usually raises the refractive index providing self-trapping and self-focusing process upon illumination of photopolymerizable liquid system [5], [6].

If a second optical fiber is aligned to the growing self-guided polymer waveguide, then light may be coupled from one fiber to another. There are few reports of such polymer bridges fabricated between two optical fibers, and the optical performance has been poor. Up to now, different strategies have been used to

construct waveguides between two fibers. Dorkenoo *et al.*, fabricated bridges as long as 1 mm but with little optical characterization [7]. Jradi *et al.*, reported an average coupling efficiency of about 65% (1.8 dB) for a polymer waveguide bridge of length 90 μm between two fibers [8]. Using a similar approach, Ecoffet and Lounnot investigated the influence of light power density on the dynamic development of coupling between two fibers via a polymer channel during the first few seconds of photopolymerization [9]. Klein *et al.*, used a two photon photopolymerization technique to build up 3D polymer structures between two fibers. This method uses an external laser source to construct a polymer bridge between two fibers, and they reported only 50% (3 dB) transmission efficiency for a waveguide of 500 μm length [10]. Mensov and Polushtaytsev in two papers reported high optical transmission long polymer waveguides fabricated between two multimode fibers [11] and two different core size single mode fibers [12]. The transmission during very early stages of polymerization was reported from the initiation of polymerization and only for up to 4 s after, and only for single wavelength 850 nm. The optical performance was not reported after rinsing, because the two fibers and photopolymerizable monomer were sandwiched between two glass plates separated by 200 μm , so the excess monomer could not be removed.

Here, we report low loss free standing polymer waveguides up to 600 μm long between two standard single mode optical fibers. We also show that the optical power required for photo-polymerization is sufficiently low that it is possible to use a xenon discharge lamp rather than a laser which allows investigation of the optical transmission over a wide range of wavelengths from visible to near IR. This broad area incoherent source ensures even illumination for writing the waveguide at wavelengths where the fiber is multimode.

II. PHOTOPOLYMER SYSTEM

The photopolymerizable system used in this study was taken from the investigations in reference [1] for fabricating polymer tips on the end of optical fibers [2], [13], [14]. The system consists of three components; a photo-initiator or sensitizer dye (eosin Y, 0.5 wt.%), a coinitiator amine (Methyldiethanolamine, 8 wt.%) and multifunctional acrylate monomer (Pentaerythritol Triacrylate) which forms the backbone of the photopolymer network. The materials were used as received from the supplier (Sigma-Aldrich) without purification. Mixtures with different photoinitiator concentrations were tested for polymer waveguide fabrication for 100–200 μm waveguide length. The best optical and mechanical performance was obtained for 0.5 wt% eosin, and this concentration was then used for all other waveguide lengths. The main advantages of such a free radical

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P. A. Mohammed is with the Department of Physics, University of Bath, Somerset, England BA2 7AY, U.K., and also with the Department of Physics, University of Sulaimani, Sulaymaniyah, Iraq (e-mail: pm442@bath.ac.uk).

W. J. Wadsworth is with the Department of Physics, University of Bath, Somerset, England BA2 7AY, U.K. (e-mail: w.j.wadsworth@bath.ac.uk).

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photopolymerizable system is its high curing rate such that the reaction takes only few seconds depending on the exposure energy because of the monomer's trifunctionality. Additionally, the photocuring is not highly influenced by impurities left inside the compound [15]. However, preparation of uniform liquid samples is challenging because the monomer, which makes up 90% of the photopolymerizable formulation, is very viscous at room temperature and it is difficult to dissolve eosin in it. Therefore, eosin was initially dissolved in the coinitiator. Also in order to obtain a uniform liquid sample, without precipitations, the coinitiator was heated ($\sim 60^\circ\text{C}$) to aid mixing then the specified proportion was added to the separately heated monomer.

The photoinitiator is sensitive to light in the range 450–550 nm, which is often provided by using lasers at 532 nm [3]. Upon the absorption of green photons, eosin Y is excited to its singlet state. Then it is either de-excited to ground state via a fast radiative fluorescence transition, or converted to its triplet state via inter system crossing. The triplet state then undergoes photoreduction by reaction with the electron donor amine. The corresponding amine in turn generates free radicals which are capable of initiating polymerization of acrylate monomers [1]. Photopolymerizations involving free radicals are extremely sensitive to oxygen quenching, such that the reaction is interrupted by reaction with oxygen molecules that are dissolved in the monomer mixture and those diffusing from surrounding atmosphere. In fact, during the first stages of irradiation photons are absorbed by the dye to create free radicals, which then react primarily with dissolved O_2 molecules until the concentration drops from $\sim 10^{-3}\text{ M}$ to nearly $\sim 4 \times 10^{-6}\text{ M}$ for acrylate monomers [16], [17]. After consuming most of the dissolved oxygen molecules, the polymerization reaction can begin. The amount of energy absorbed by the solution at the early inhibition stage is known as the threshold energy [1]. Beyond this energy, further free radicals generated can contribute to the polymerization process. The polymerization process is also very sensitive to oxygen molecules diffusing from the surroundings. The quenching effect of diffused oxygen is more dominant at the sample air interface. Therefore the final shape of a written polymer structure is highly affected by the curing position relative to surrounding atmosphere. The self-guiding process has been referred to as a quasi-solitonic behaviour and in the initial stages of writing the guided beam produces nodes in the written waveguide [7]. However the effect is not long lasting because of the rapid conversion of the irradiated monomer refractive index under the action of photopolymerization [2]. The node formation has been numerically predicted by Hocine *et al.*, using beam propagation method modelling through a medium where the refractive index increases with time [13], and it is observed in the experiments reported here, Fig. 1.

Usually the light required for photopolymerization is provided by a coherent laser beam, as this is easy to couple into an optical fiber core and provides high power density. However we show here that the process is also possible for broadband incoherent light sources such as laser driven xenon source. The broad spectral range of absorption of the photoinitiator is able to gather sufficient energy from this low intensity source to be able to reach the threshold for initiating photopolymerization.

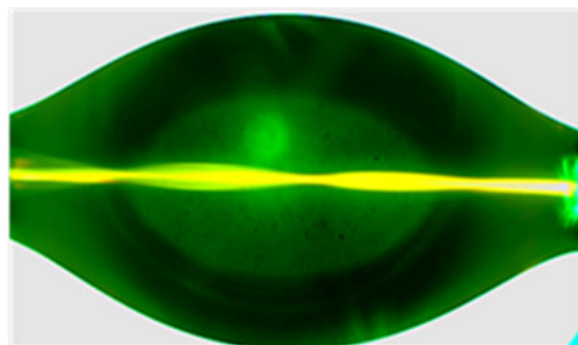


Fig. 1. Optical micrograph of the initial stage of photopolymerisation by light emerging from the fiber on the right. The guided beam produces nodes in the written waveguide during early stages of photopolymerization.

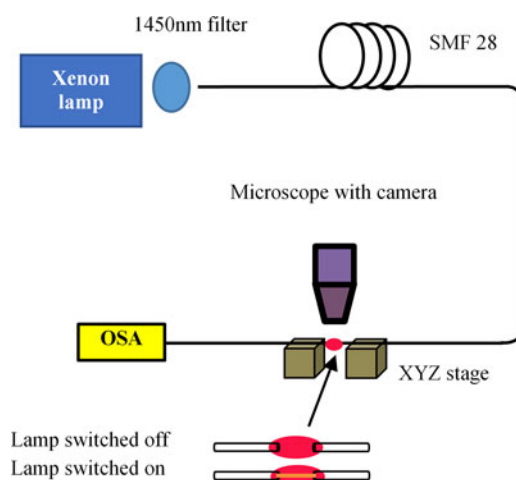


Fig. 2. Experimental system for photo-polymerization and optical characterization. OSA, optical spectrum analyzer. The magnified diagram of the fiber ends corresponds to the micrographs of Fig. 3(a).

In our experience the required power for photopolymerization of the tiny cross-section of a polymer waveguide is 2 to 20 μW , but there are reports using powers as low as 0.1 μW [3], [18]. An incoherent beam is a great advantage as the writing wavelength may be much shorter than the operating wavelength, meaning that the fiber is likely to be multimode at the writing wavelength. A narrow band laser source with high beam quality will excite a combination of modes which will potentially provide a varying beam pattern at the output of the fiber where the waveguide is to be written. This can be mitigated by careful coupling or by building a mode filter [19] into the fiber, but it is much more simply eliminated using a spatially and spectrally incoherent source. The broad area source ensures stable equal excitation of all the fiber modes, whilst a broad wavelength band washes out the intensity fluctuations caused by changing interference between modes as the fiber is moved. In this study a laser-driven xenon discharge lamp (Energetiq EQ-99) was used, providing a bright broadband source of light from <300 to $>2000\text{ nm}$. An ordinary xenon discharge lamp would also provide the required power density, but the laser driven lamp provides high spatial stability of the small discharge which is important for good coupling into the fiber. This light source can serve a

double purpose of photo-polymerization and optical transmission testing, allowing reliable loss measurements for the waveguides. When quoting a single loss figure for a waveguide the measured loss was averaged between 1500–1600 nm, in the single mode region of the SMF 28e fiber.

III. WAVEGUIDE BRIDGE FABRICATION

The polymer waveguide bridge fabrication commenced with a single piece of fiber (*Corning*, SMF 28e) as shown in Fig. 2. Light from the xenon discharge lamp was coupled into the fiber and a baseline transmission spectrum was recorded using an optical spectrum analyzer (OSA, *Ando* AQ-6315E). The input and output alignment was then fixed to allow all spectra during and after fabrication to be referenced to this baseline, allowing accurate measurement of the optical performance. This initial spectrum also showed that the optical power available for photoinitiation of the polymerization was -35 to -40 dBm/5 nm at 500 nm, giving a few microwatts total power over the absorption bandwidth of the eosin Y. The fiber was then cleaved in the middle and the two new ends were aligned with a set distance between them (40 to 600 μm). The transverse position was optimized by observing the transmitted power at 1550 nm (where the fiber is single mode) received by the OSA. Once transmission at 1550 nm was maximized, the spectrum was recorded as the air gap transmission between fibers. Next a long pass, 1450 nm, filter (*Thorlabs*, FEL 1450) was placed between the xenon lamp and the input fiber to prevent premature photopolymerization. A small drop of the monomer mixture was put between two fibers to make a liquid bridge between them. The positioning of the fibers was adjusted again to get maximum transmitted power at 1550 nm since deposition causes some misalignment. By removing the optical filter photo-polymerization started, Fig. 3(a). The progress was monitored by taking repeated transmission spectra, and optical micrographs. An initial waveguide bridge formed very rapidly between the two fibers but full formation took about 5 min of photocuring. The remaining uncured monomer was rinsed off using ethanol, leaving an exposed polymer waveguide bridge rigidly attached between the fiber ends as an extension of the fiber core, as shown in Fig. 3(b). The rinsing step is crucial in the bridge fabrication because the crosslinking degree of the polymer is still low so that imposing tiny extra pressure may break the bridge especially at the fiber/polymer interface. A final transmission spectrum was recorded for the finished waveguide bridge. Fig. 4 shows the loss spectrum of the 400 μm air gap, the waveguide bridge during formation and the final rinsed polymer bridge, referenced to the transmission of the initial single fiber before cleaving. There are abrupt features associated with high order mode cut-offs at 900–1100 and 600–800 nm. The absorption of the eosin Y photoinitiator between 400 and 550 nm is clearly visible in the initial spectrum during polymerization, but decreases as the dye is bleached over the 5 min exposure. The final polymer waveguide bridge shows little residual absorption and a low loss ~ 0.5 dB across the whole spectral range; from 380 nm where the germanium doped step-index fiber starts to have high transmission to the upper limit of the OSA at 1750 nm.

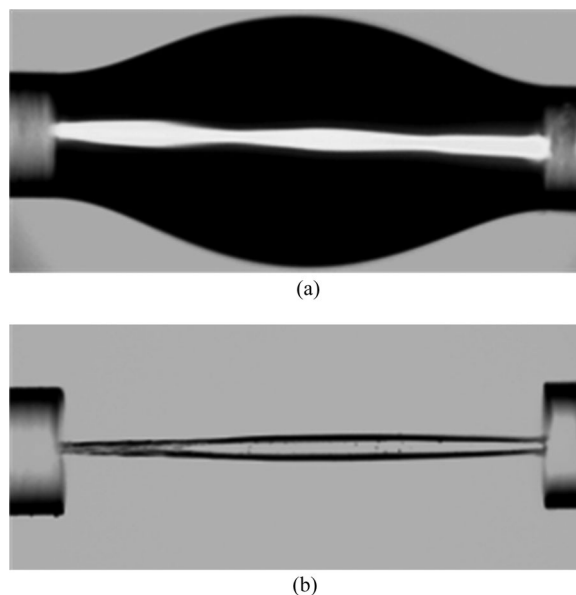


Fig. 3. Optical microscope images of formation of a polymer waveguide bridge: (a) Fluorescence shows the region where photopolymerization is in progress. Light is incident from the right-hand fiber. (b) 600 μm long polymer bridge between two fibers, 1.26 dB loss at 1550 nm.

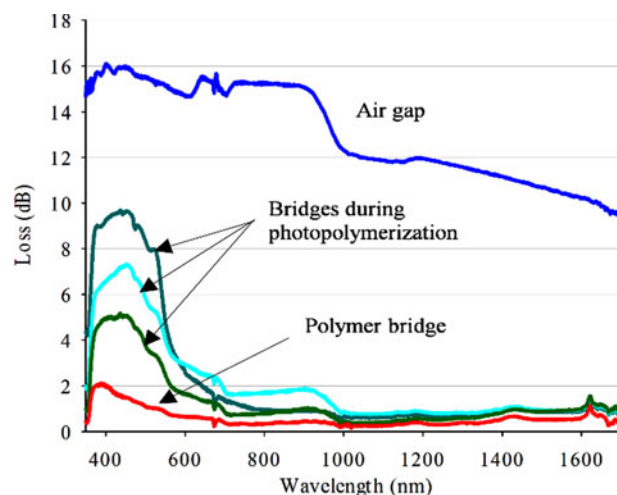


Fig. 4. Loss as a function of wavelength associated with 400 μm air gap and polymer waveguide bridges at different stages of formation.

IV. WAVEGUIDE GEOMETRY AND FEATURES

Photoinduced waveguides imprint the profile of the guided mode through the photopolymerizable liquid system. Accordingly, the shape and size of the polymer waveguide constructed between two fibers is determined by the writing beam emerging from the fiber core, its shape and power and less prominently the exposure time. Additionally, the final shape of the channel substantially depends on the deposited liquid drop shape connecting the two fibers before polymerization. The impact of drop shape mainly arises from the possibility of oxygen diffusion from the surrounding atmosphere. Photopolymerization will overcome oxygen inhibition more easily in reaction sites where the

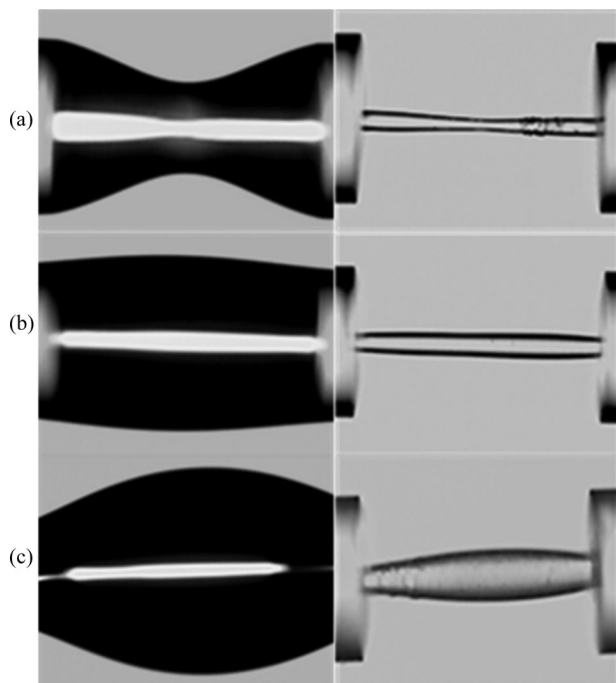


Fig. 5. The effect of oxygen diffusion and deposited drop shape on the final polymer bridge shape. Length $240\ \mu\text{m}$. Left column; optical micrographs during illumination and polymerization (light is incident from the right-hand fiber). Right column; optical micrographs of the waveguide bridges after rinsing.

diffusion length of oxygen is longer. Therefore polymerization will occur at lower power in a larger drop which leads to a larger waist because the threshold energy for photopolymerization is reached in the wings of the mode as well as the center. The influence of pre-polymerization drop shape on the final waveguide shape is illustrated in Fig. 5 for three different liquid drop shapes with all other parameters unchanged. A small hour-glass shape drop (see Fig. 5(a)) results in a narrow waveguide bridge, with a central narrower waist, a large bubble shaped drop (see Fig. 5(c)) results in a wide bridge with a central bulge, and a straight drop (see Fig. 5(b)) results in a uniform waveguide bridge. If the rate of radical production were changed significantly, for example with light intensity or initiator concentration, the balance with oxygen quenching would also change resulting in different waveguide shapes.

The lowest loss ($\sim 0.5\ \text{dB}$) was achieved with the uniform waveguide formed in a straight drop, Fig. 5(b). Because of this, a straight drop was used wherever possible in fabrication, although for $400\text{-}\mu\text{m}$ length and longer the drop shape was harder to control and a more bubble shaped drop was used. The other shapes showed higher loss of $0.5\text{--}1\ \text{dB}$ for Fig. 5(c) and $1\text{--}1.5\ \text{dB}$ for Fig. 5(a). This means that with some loss penalty one can adapt the waveguide shape for different applications; for example using a waveguide with a narrower waist to enhance evanescent interactions with the guided mode in a sensor application.

To form similar waveguides using the high power collimated beam from a laser source the curing time is in the range of few seconds in our experience and previous reports [8], [12].

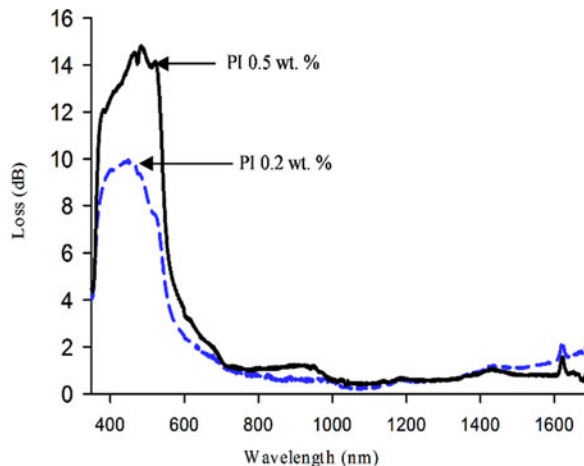


Fig. 6. Absorption of two different photoinitiator concentration samples during the early stage of photopolymerization. The gap between fibers is $600\ \mu\text{m}$.

Conversely, the curing time needed to form waveguides with high transmission using a xenon discharge lamp was several minutes. This exposure time is much greater than the time necessary for building up the polymer bridge itself, however the polymer waveguide needs to be over exposed in order to enhance its mechanical properties to resist the pressure of rinsing and shrinking caused by ethanol so as to optimize its optical transmission performance. A short exposure leads to narrow bridges, since the oxygen inhibition is dominant and photopolymerization happens at only the brightest region of the guided mode while at the edge of the beam the energy cannot reach the polymerization threshold [2].

The concentration of $0.5\ \text{wt}\%$ eosin Y was chosen for formation of waveguides up to $600\ \mu\text{m}$ length. For the longest waveguides in this study there was a degradation of the waveguide quality towards the output end. Fig. 6 shows the spectrum immediately after illuminating the liquid bridge for two different eosin Y concentrations. It shows that the absorption depends on the photoinitiator concentration, and that for the selected $0.5\ \text{wt}\%$ concentration sample only 5% of the incident light reaches the end of the waveguide before the dye is bleached. This large difference in absorption however does little to change the overall transmission or shape of the waveguide bridge (see Figs. 6 and 7). The only observable difference is in the shape of the surface of the waveguide bridge at the output end. In all examples longer than $400\text{-}\mu\text{m}$ surface structure appears at the end of the waveguide. In Fig. 7 there is a difference in the point at which the surface structure appears, with Fig. 7(a) showing a longer clean waveguide, however this effect is not attributed solely to the eosin Y concentration as repeated fabrication with the same monomer mixture yielded different results. The uneven surface may arise from modal effects as the fiber has several modes at the excitation wavelength, or may be the onset of nonlinear instabilities as studied by [13]. This phenomenon has not been noticed with waveguides written at the end of multimode waveguides using high power lasers [11], [20], [21], which suggests that either the small physical size, or few-moded nature of the fiber are important here.



Fig. 7. 600 μm bridges associated with two different eosin concentration samples showed in Fig. 6. For photopolymerization, light was incident from the right-hand fiber. (a) 0.5 wt.%, (b) 0.2 wt.%.

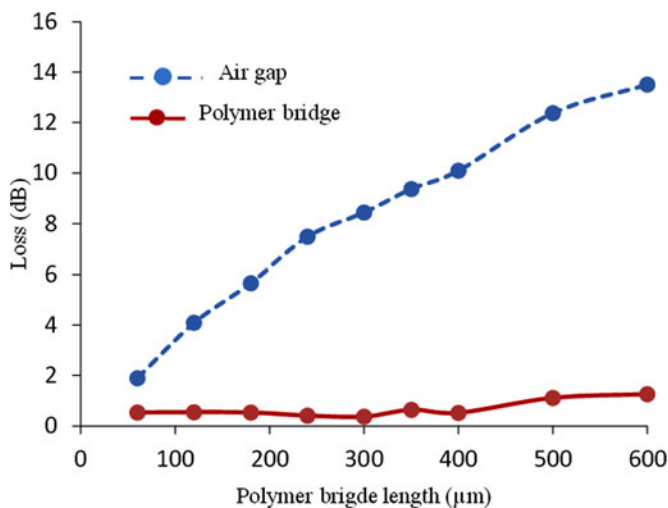


Fig. 8. Loss recorded between two aligned fibers with air between (dashed line) compared with loss in a polymer waveguide bridge (solid line). Data taken from spectra as in Fig. 4 averaged from 1500–1600 nm, in the single moded region of the fiber.

V. OPTICAL TRANSMISSION PERFORMANCE

Nearly all the polymer waveguides fabricated showed similar broadband, low loss transmission, and there was no significant increase of the loss as the waveguide length increased to about 600 μm . The polymer channels guide light very efficiently, especially when compared with an air gap between two fibers. This comparison is illustrated in Fig. 8, showing a loss between 0.5 and 1.26 dB for bridges 40 to 600 μm long in the spectral region where the fiber is single moded. At other wavelengths the attenuation was similar, even at shorter wavelengths where the fiber is multimode. For each length there was a target of 0.5 dB transmission loss, and one or two low-loss waveguides were fabricated, with the better loss presented in Fig. 8. The loss evolution with increasing the bridge length remains quite small around 0.5 dB up to 400 μm , but it is clear from Fig. 8 that there is a relatively rapid increase in loss with 500 and 600 μm bridges. This is probably a consequence of the poor surface morphology of the ends of these longer bridges, as seen in Fig. 7. Other factors may also have contributed in this

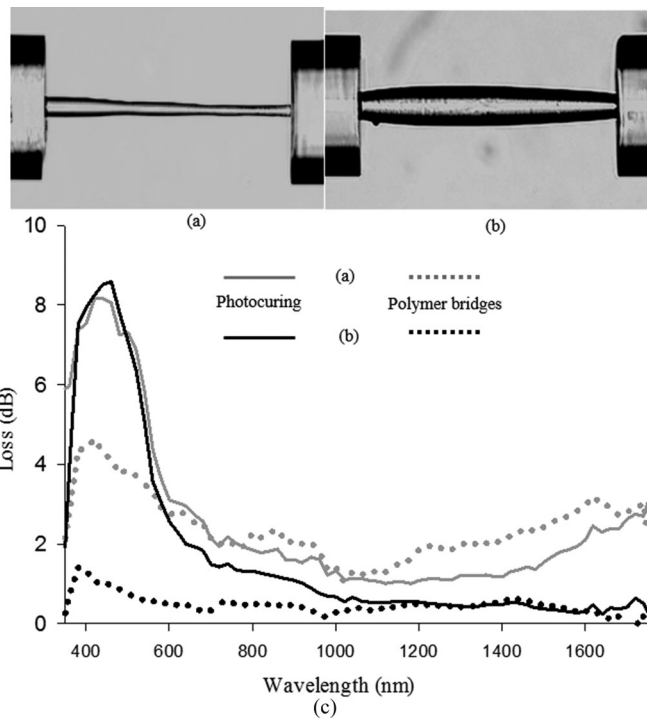


Fig. 9. For a straight liquid drop and 300 μm length, a narrow bridge results from low exposure (a) and a wide bridge results from high exposure (b). In both (a) and (b) the light is incident from the right hand fiber. (c) Optical transmission associated with the bridges shown in (a) grey lines and (b) black lines. Solid lines are spectra taken during the first 90 s of polymerization, dotted lines are the finished waveguide bridge after rinsing.

efficiency falling. Transverse shifts of the fabricated bridge are more likely to happen for long bridges during rinsing. Also for such a large gap the initial alignment by maximization of measured at 1500 nm is very difficult because even with moving one of fibers by several μm the transmitted power does not change, so the waveguide growing from one core may be misaligned from the receiving fiber.

In all of the bridges there are several possible mechanisms for attenuation after polymerization is complete. Firstly there are bulk effects in the material itself; residual, unbleached, absorption from the initiator (particularly at short wavelengths) or scattering from bulk impurities. Secondly with insufficient exposure waveguides may not be sufficiently well attached to the ends of the fibers. Finally the shape of the waveguide affects the propagation of waveguide modes. For single mode transmission, the mode of the input fiber must match the mode of the waveguide bridge at the input and output. Changes in the bridge along its length (as in Fig. 5) must be slow to allow the waveguide mode to adapt adiabatically. With the high index contrast of the rinsed waveguides, surface scattering may also be significant. This may be important in the longer bridges (see Fig. 7) and also may depend on waveguide size, with smaller waveguides having more interaction of the guided mode with the surface.

In order to demonstrate the effects of mode mismatch and surface scattering, a 300 μm long thin bridge like that shown in Fig. 9(a) was fabricated by reducing a beam power to half and

shortening exposure time from 5 to 1.5 min which is the time needed to take the whole spectrum by the OSA.

The optical transmission performance of this bridge is shown in Fig. 9(c), compared to a wider bridge (see Fig. 9(a)). From the transmission in Fig. 9(c) one can see that the optical performance of the thicker bridge is much better than that of thinner one, although the difference is smaller during photopolymerization when the bridges are still surrounded by uncured monomer liquid and so have a smaller refractive index contrast. The fatter bridge has a transmission loss of 0.4 dB, (90% transmission), so all of the loss mechanisms are small. This means that the smaller waveguide will have a relatively large mode field mismatch for coupling from and to the fiber mode, and is also likely to have a larger overlap of the guided mode with the waveguide surface, leading to increased surface scattering. The combination of these effects gives the high loss shown in Fig. 9(c).

VI. CONCLUSION

A new technique for fabricating long polymer waveguides between two aligned optical fibers was investigated. Polymer waveguide bridges up to 600 μm long showed high optical transmission with less than 1.26 dB loss (and less than 0.5 dB over 400 μm) over a broad spectral region from the visible to the near infrared. The fabrication process involved spatially controlled photopolymerization of a liquid monomer system deposited between two fibers using a broadband incoherent lamp.

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Pshko A. Mohammed was born in Kalar, Iraq. He received the Diploma and M.Sc. degrees from the University of Sulaimani, Sulaymaniyah, Iraq, in 2003 and 2007, respectively. He is currently working toward the Ph.D. degree from the University of Bath, England, U.K. His research interests include photopolymer materials and microstructured polymers integrated with optical fibers.

William J. Wadsworth received the B.A. and D.Phil. degrees from the University of Oxford, Oxford, England, U.K., in 1993 and 1997, respectively. He joined the University of Bath, England, U.K., in 1999, where he is currently a Reader in physics. His research interests include new lasers and light sources, particularly using Photonic Crystal Fibres PCFs, with applications from fundamental metrology and quantum information to laser machining and imaging for medical and life sciences.