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Self-phase modulation and spectral broadening in millimeter long self-written polymer waveguide integrated with single mode fibers

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ABSTRACT

Polymer waveguide bridges up to 1.2 mm in length were optically written between two single-mode optical fibres. Optical Nonlinearity of polymer waveguide was measured by coupling a high power ultra-short pulsed laser. Before waveguide fabrication fiber ends were treated by adhesion promoter which covalently bond to both the silica fibre and the photopolymer, also photopolymerization was conducted from both fibres. The new techniques improve both the mechanical properties and optical transmission of polymer bridges. The optical insertion loss was 1.1 dB for the longest waveguides. A considerably long interaction length of polymer waveguide allows spectral broadening and self-phase modulation features to occur in response to the high power laser propagation through the polymer bridges. The spectral broadening in polymer waveguide was much broader than that of 1.5 m plain fibre. The ultrafast nonlinearity of the polymer waveguides was determined to be of the order of 10^3 times the nonlinearity of silica.

1. Introduction

Nonlinear waveguides have been an interesting field for intense research in the past two decades due to a wide range of applications from ultra-fast optical switching to supercontinuum generation. Recent advances in this field demands materials with appropriate optical characteristics primarily strong nonlinearity and low propagation loss. Moreover, in hybrid systems the material must be efficiently integrated with the system to provide the desired requirements [1]. Various nonlinear effects have been previously detected in nano- and micro-waveguides such as silicon on insulator [2,3], silicon nitride [4] silica and chalcogenide glasses [1,5], crystals [6,7]and polymer waveguides [8,9]. Self-written polymer waveguide fabricated between two single mode fibres can be a possible entrant for optical nonlinearity applications as it can provide high optical transmission and self-alignment with optical fibre [10]. Contrary to free space, where a substantial amount of guided beam diverges. In single photon photopolymerization the propagation of Gaussian beam in photopolymerizable liquid deposited between two aligned fibers leads to formation of solid polymer channel which confines a guided beam with in the polymer waveguide [11]. The guided beam throughout spatial polymerization leads to form a straight polymer bridge as a consequence of the rapid conversion of monomer from liquid state into a solid polymer as indicated by fluorescence region where reaction happens as illustrated in Fig. 1. The initially diffracted beam develops a region of increased refractive index which leads to confining a beam into a polymerized channel which has been made by the beam itself along with the propagation axis [12,13]. This approach also guarantees self-alignment between polymer channel and optical fiber cores and reduces the misalignment uncertainty.

The process is simple and allows us to fabricate polymer channels with various cross sectional diameter by adjusting curing beam intensity and exposure time. This technics is particularly efficient and do not need any 3D control as it may be necessary for two photon photopolymerization [14]. Self-written waveguide has shown potential for some applications such optical and printed circuit interconnections, splicing, sensing, scanning near field optical microscopy, coupling and integrated optical devices [15–17].

Here we modify our previous technique [10] to fabricate millimetre long freestanding waveguide with high transmission efficiencies, we also investigate nonlinear response of these waveguides under high power short pulse laser and optical nonlinearity response of a milimiter long waveguide. The longest waveguide we fabricated in the previous paper was 600 μm, which could not handle a certain peak beam power to observe clear spectral broadening. The nonlinear response in polymer structures mainly occurs because of Kerr effect or third order nonlinear response. The phenomenon implies primarily self phase

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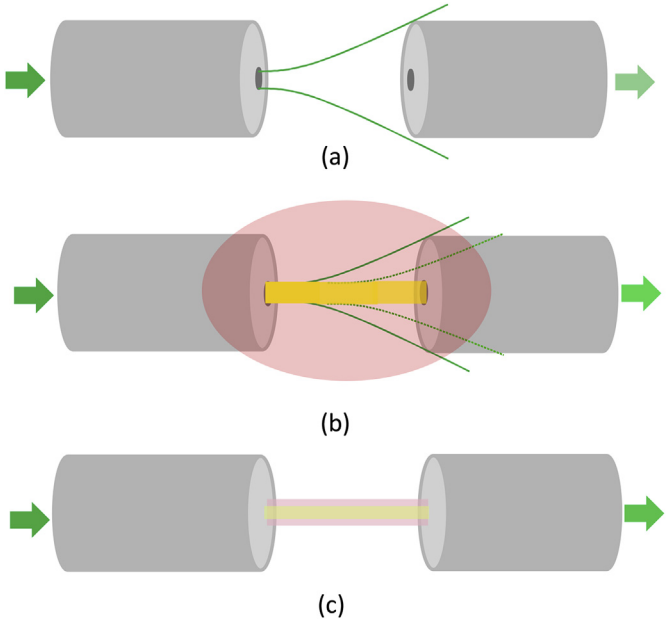

Fig. 1. Schematic explanation of self-written polymer waveguide formation. (a) Free space coupling, some light will diffract and coupling loss increases with air gap between two fibres. (b) Light induces polymerization of monomer droplet deposited between two fibers, yellow strip is a fluorescence emission results from excited photoinitiator molecules transition from higher energy state to ground sate and indicates the boundary where the polymerization happens. (c) Polymer waveguide appears between two fibres after washing off unaffected part of the droplet, light is confined in the polymer bridge. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

modulation (SPM) which may also be accompanied with two photon absorption (TPA) [1,3]. Although these effects may be undesirable in some applications, but they also play a significant role in building all-optical devices. Understanding the nonlinear properties of polymer waveguides is thus important in future applications associated with integrated photonic [3].

We also demonstrate SPM features occurred in response to high power pulsed laser propagation through the polymer structure. The phenomenon happens because of refractive index dependency on the guides pulse's intensity which in turn causes spectral broadening to ta take place with the pulse whereas the pulse temporally unchanged. The waveguide showed considerably high transmission efficiency over broadband spectrum from visible to near IR which qualified polymer bridge for nonlinearity investigations. We qualitatively demonstrated nonlinear effects occurred in the polymer waveguide through pulse broadening and SPM and the quantitatively calculate nonlinear parameter in such polymer structures can be larger by factor of 10^3 from silica fiber.

2. Waveguide fabrication

Fabrication of the polymer waveguides using photopolymerizable system consists of acrylate monomer (Pentaerythritol Triacrylate - PETA) 91.5 wt%, a coinitiator (Methyldiethanolamine - MDEA) 8 wt% and a photoinitiator (Eosin Y) 0.5 wt%, followed substantially the same process as our previous results [10]. However, we encountered some limitations to extend the bridge length to the range of millimetre. The limitations originated from fabrication factors and nature of materials such as curing beam power, surface tension, photopolymerizable system viscosity and the fragility of polymer bridge due to lack of proper adhesion joint between polymer and silica fiber at the interfaces.

To construct a millimetre waveguide between two single mode fibers (*Corning*, SMF 28e), these barriers should have been overcome. Firstly, the light beam power declines considerably at the tail of bridges when curing was done from one fiber resulting in deteriorated surface and fragile polymer channel. This one was overcome by coupling both fibers to the light source and curing from both fibers. A fiber photonic lantern [18] was fabricated in order to couple light equally into two single mode fibers from the light source. Secondly, the fiber ends were treated with adhesion promoter (3-(trimethoxysilyl) propyl methacrylate) (3-TPM) by immersion in the liquid at room temperature. The adhesion promoter was selected with appropriate functional groups to bond to the silica surface also to take part in the polymerization process. 3-TPM through methoxysilyl groups will bind to available Si-O-H sites on the fiber by a condensation reaction. While the acrylate tail of the 3-TPM is then available to take part in the photopolymerization of the waveguide. Finally, the fiber sizes and monomer viscosity do not allow us to put a liquid drop longer than 750 µm even with heavy lubrication. This barrier was eliminated by inserting fibers into capillaries (ID/OD 300/1000 µm). The capillaries have two main advantages; the length is not limited by the size of the drop that can be maintained between two fibers and the reacting area is protected against diffusing oxygen from the drop/air interface to the polymerization reaction site - oxygen being a strong quencher of free radical photopolymerization [19]. Fig. 2 shows consecutive stages of waveguide formation by illumination from both fibers. Upon photopolymerization, the refractive index increases to 1.52 for polymer bridge, whereas the refractive index of monomer system is 1.48. Polymerization development is shown in (Fig. 2 (a - f)) from photopolymerization initiation and at later times then the last one is a rinsed polymer waveguide after 5 min of photocuring. The polymer bridge is extended between the cores of two fibers with average cross sectional diameter about 40 µm. Although, the physical diameter of the polymer waveguide is larger than the core of the fiber, but the overlap integral of fundamental mode between the fiber and polymer must be close to unity because the observed insertion loss is very small. Therefore, we can argue that the effective area of the fundamental mode through the polymer waveguide is approximately equivalent to the core area. In addition, the significant amount of the

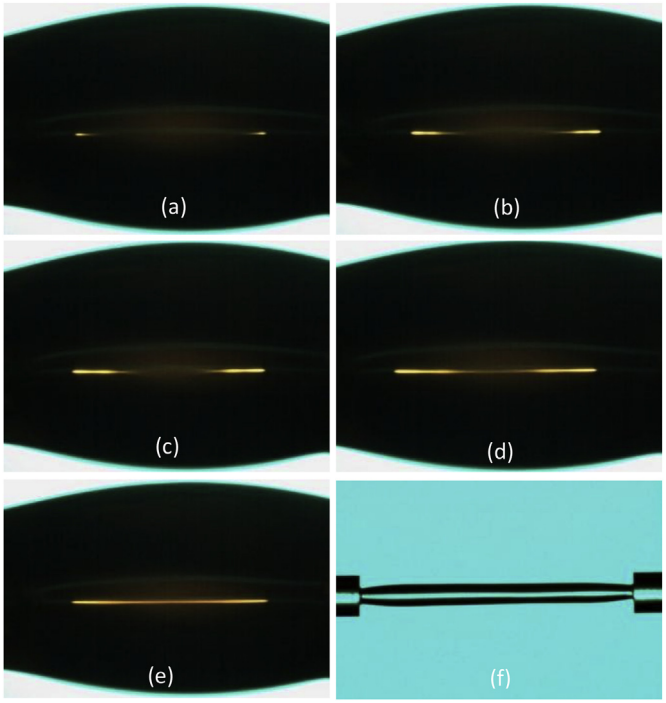

Fig. 2. Optical microscope images of a 1.2 mm long photopolymer waveguide fabrication. a) Photopolymerization triggered, then at b) 2.5 s, c) at 8.5 s, d) 15 s, e) 2 min, and f) after rinsing.