High-Speed Performance of 140 cm-long Flexible Multimode Polymer Waveguides Link Supporting 1 mm-radius Bend

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Abstract: We achieved 30 Gb/s error-free transmission using 140 cm-long flexible multimode polymer waveguides link with a measured bandwidth of 42 GHz·m. Bandwidth degradation is negligible under a bending radius of 1 mm with 3-turn twists.
OCIS codes: (200.4650) Optical Interconnect; (130.5460) Polymer waveguides;

1. Introduction

Multimode polymer waveguides, which have good compatibilities with both PCBs and fiber optics, are considered to be one of the promising transmission media for implementing high-speed board-level optical interconnects. Transmission loss of multimode polymer waveguides can be lower than 0.05 dB/cm at 850 nm [1,2]. They can be coupled to and from graded-index (GI) multimode fibers with low coupling loss. Moreover, flexible polymer waveguides can withstand bending, twisting and even stretching. However, signal degradation due to their multimode nature leaves concerns on both transmission data rate and applicable distance. Studies on the effects of bending on the loss, crosstalk and bandwidth performance have been carried out with a flexible waveguide length of 24 cm [3]. Although the data transmission rate of 25 Gb/s per channel has been reported on flexible multimode polymer waveguides, these demonstrations involve straight waveguides with length less than 20 cm [4,5]. 40 Gb/s data transmission with a minimum bending radius of 4 mm is realized on a 1 m-long flexible spiral waveguide [6].

In this paper, we demonstrate bandwidth measurement and 30 Gb/s data transmission of connectorized flexible multimode waveguides link with maximum length of 180 cm. We observed that the pulses transmitted in the waveguides link broaden linearly with the increase of its length. Moreover, bandwidth degradation is negligible under 1 mm bending radius with 3-turn twists of 140 cm-long flexible waveguides and an error-free transmission 30 Gb/s data transmission has been achieved. Our results show that the flexible multimode waveguides have both excellent optical and mechanical properties and they are suitable for high-speed optical interconnects application especially those have a tough requirement on flexibility.

2. High-speed performance evaluation

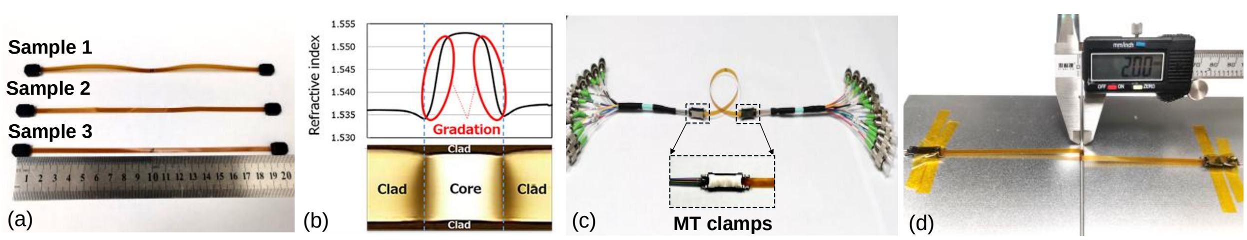

Fig. 1. (a) The flexible waveguides samples with MT connectors; (b) Measured index profile of the waveguide; (c) Flexible waveguide connected with fiber ribbons; (d) Flexible waveguide under a bending radius of 1 mm with 3-turn twists.

Flexible polymer waveguides are fabricated using polynorbornene by proprietary "Photo-addressing" technique proposed by Sumitomo Bakelite Co., Ltd. [7]. As shown in Fig. 1(a), three waveguide samples with the length of 20 cm and core sizes about 44×46 μm are fabricated under the same conditions. Each waveguide sample has 12 channels and the waveguide pitch is 250 μm. The refractive index profile in the horizontal direction is GI profile and step-index (SI) profile in the vertical direction as shown in Fig. 1(b). Specifically, the refractive index of core is 1.553 and the horizontal and vertical cladding are 1.535 and 1.517, respectively. Detailed waveguide fabrication processes are reported in [8]. MT clamps are employed to secure the connection of the two MT connectors as shown in Fig. 1(c). The waveguides can be bent down to 1 mm radius without any cracking or delamination as shown in Fig. 1(d).

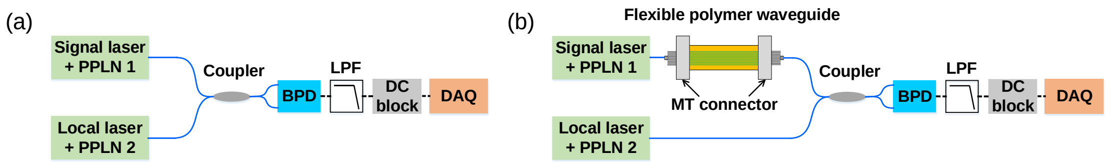

Fig. 2. Experiment setup for measuring the waveguide bandwidth of (a) back-to-back link and (b) waveguide link.

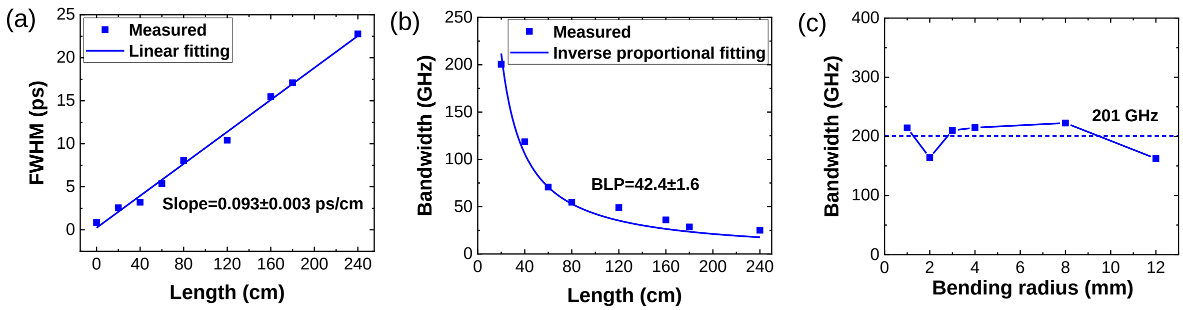

Fig. 3. (a) The FWHM and fitting curves of different lengths; (b) The measured bandwidth of different lengths. (c) The measured bandwidth of waveguide bending with length of 20 cm.

The bandwidth of flexible polymer waveguides is estimated using our proposed direct time-domain measurement based on optical sampling technique [9]. The experimental setup for measuring waveguide bandwidth is shown in Fig. 2. Two mode-locked lasers with the center wavelength of 1560 nm are employed as signal and local lasers. The repetition rates of both lasers is about 250 MHz, and there is a frequency difference of about 0.3 kHz between them. Two Periodically Poled Lithium Niobate (PPLN) crystals are used to produce frequency doubling pulses at the wavelength of 780 nm. The pulses after waveguides interfere with the local pulses at the multimode 3 dB coupler and then detected by a balanced photo-detector (BPD). Finally, the signal is sampled by an oscilloscope.

We measure the dispersion-induced pulse widths and calculate the bandwidth of waveguides with different lengths. To make full use of the advantage of MT connectors mounted on the waveguides, the different lengths of flexible waveguides are obtained by connecting different channels in the same waveguide sample with MT-MMF ribbon fiber jumpers. In order to maximally reduce the experimental error, the lengths of the MT-MMF ribbon fiber jumpers are only 15 cm. Gaussian curves are adopted to fit the envelopes of the original pulses. As shown in Fig. 3(a), the full-width-at-half-maximum (FWHM) of pulses with different waveguide lengths and the corresponding linear fitting curves are obtained. The slope of the fitting curve, which represents the group delays of flexible waveguide, is 0.093 ps/cm. As expected, The FWHM has excellent linearity with waveguide length. It can be expected that the average is taken more times, the standard deviation can be smaller. The estimated 3 dB bandwidth is obtained by subtracting the Fourier transform of the input pulse and the output pulse as shown in Fig. 3(b). Different from our previous work [9], we directly take the Fourier transform of the envelopes rather than fitting curves of envelopes. The inverse proportional function is used to fit the relationship between the measured bandwidth and the waveguide length. The proportional coefficient, which is the bandwidth-length-product (BLP) of the flexible waveguides, is 42 GHz·m. The bandwidth of 20 cm-long flexible waveguides under flexure is also investigated as shown in Fig. 3(c). There is no significant bandwidth degradation with the flexure waveguide under a bending radius of 1 mm with 3-turn twists. The obtained results are in agree with the results obtained from previous bandwidth studies on multimode waveguide bends on rigid substrate [9].

In order to evaluate the practical high-speed transmission performance, NRZ transmission at a data rate of 30 Gb/s is conducted. The experimental setup is shown in Fig. 4. Light from the DBR-LD at 850 nm is transmitted to a 25 GHz intensity modulator. Considering the withstand power of the modulator, the maximum output power of the modulator is 4 dBm. A multimode variable optical attenuator (VOA) is used for optical power adjustment and the light from the VOA is detected using a 22 GHz photodiode (PD). After being amplified by a 50 GHz RF amplifier, the electrical signal is transmitted to the BERT or a digital sampling oscilloscope.

Received eye diagrams for the B2B link and straight waveguides with different length of 60 cm, 120 cm, 140 cm, and 180 cm are shown in Fig. 5(a). Data transmission studies on the relatively-long flexible waveguide with a length of 140 cm under flexure are also conducted. Open eye diagrams are obtained for the B2B link and all waveguide with different lengths. Minimum eye closure can be observed due to additional dispersion and noise when the waveguide is inserted into the link. Although this phenomenon is more obvious with the increase of waveguide length, an open eye diagrams are still observed when the waveguide length reaches 180 cm. In addition, the shapes of the eye diagrams are almost unchanged with the decrease of the waveguide radii, even to a severe flexure with 1 mm radius and 3-turn twists as shown in Fig. 5(b). BER measurements are also carried out on all optical link. Error free (BER<10^{-10}) data transmission is achieved over the waveguide link up to 140 cm in length as shown in Fig. 5(c). Because the measured BER is shown 0 in the used BERT when BER<10^{-12}, BER<10^{-10} is considered as error free transmission here. The power penalties for a BER of 10^{-9} are found to be about 0.6 dB, 1.3 dB, and 1.3 dB for waveguides with lengths of 60 cm, 120 cm, and 140 cm, respectively. The insertion losses of straight waveguides are shown in Table 1. Taking into consideration the maximum output power of the modulator of 4 dBm, the averaged received power of error free (BER<10^{-10}) transmission, and the additional 1 dB loss in the link such as connecting loss, the power margin can be estimated. For the 180 cm-long waveguide link, the minimum BER is 3.6×10^{-8} due to relatively large insertion loss of 13.5 dB. It is also well below the forward error correction limitation. Table 2 shows excess bending loss and power margin of the 140 cm-long flexure waveguides. As shown in Fig. 5(d), BER curves also show that there is no serious degradation of transmission performance when the waveguides have severe flexure under a bending radius of 1 mm with 3-turn twists.

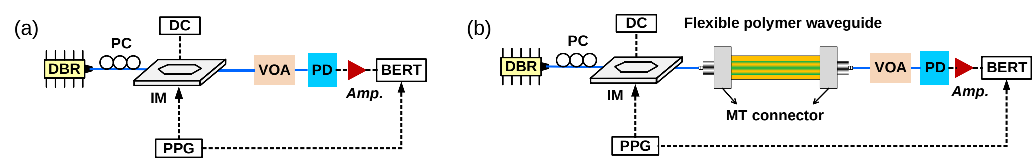

Fig. 4. Experimental setup for high-speed data transmission of (a) back-to-back link and (b) waveguide link.

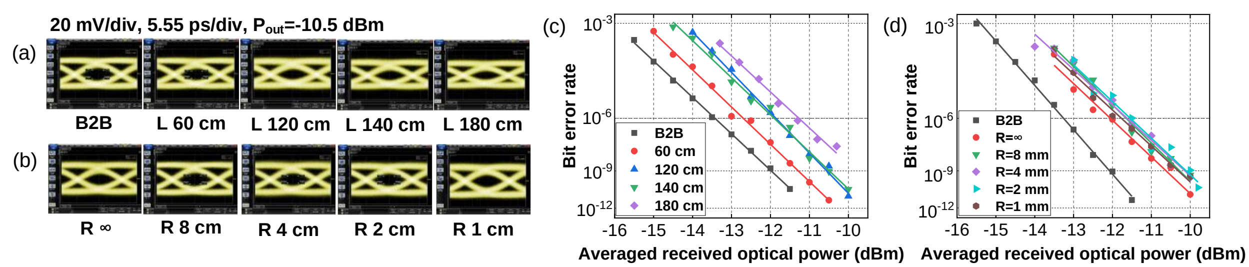

Fig. 5. (a) Received eye diagrams for waveguides with different lengths and (b) 140 cm-long waveguides under flexure; (c) BER curves for the B2B and waveguide link with different lengths and (d) 140 cm-long waveguide link with different bending radii.

Table 1. The Insertion Loss and Power Margin of Straight Waveguides

Length (cm)	60	120	140	180
Insertion loss (dB)	3.55	8.39	11.10	13.54
Power margin (dB)	10.45	4.61	1.90	-1.60

Table 2. The Excess Bending Loss and Power Margin of Waveguides

Radius (mm)	∞	8	4	2	1
Excess bending loss (dB)	0	0	0.11	0.13	0.74
Power margin (dB)	1.9	1.9	1.79	1.77	1.16

3. Conclusions

We achieved 30 Gb/s error-free transmission using 140 cm-long flexible multimode polymer waveguides link with a measured bandwidth of 42 GHz·m. Bandwidth degradation is negligible under a bending radius of 1 mm with 3-turn twists. The results demonstrate the excellent optical and mechanical properties of flexible waveguide and highlight its practical development in real world systems.

4. Acknowledgements

This work is supported by the National Key Research and Development Program of China (2019YFB1802900) and The Major Key Project of PCL (PCL2021A14).

5. References

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