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Laser-direct writing of single mode and multi-mode polymer step index waveguide structures for optical backplanes and interconnection assemblies

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Abstract

A laser direct writing (LDW) method is implemented as a cost efficient polymer waveguide (WG) fabrication method for prototyping large substrates for optical backplanes and optical interconnection assemblies. The LDW setup utilizes a 3-axis air-bearing motion platform to reduce WG fabrication error to within ±0.15 μm. A UV laser diode coupled single mode fiber with a focusing lens module is capable of LDW WGs at both multimode (50 μm) and single mode (6 μm) dimensions. Correlation between LDW parameters and fabricated WG dimensions using Dow Corning® OE-4140 UV-Cured Optical Elastomer ($n_{core} = 1.5142$, $n_{clad} = 1.5064$) is discussed theoretically and confirmed experimentally for both applications. A theoretical model is developed and utilized for producing LDW multi-mode (0.04 dB/cm, $\lambda = 850$ nm) and single mode (0.55 dB/cm, $\lambda = 1310$ nm) WGs. Measured propagation losses of LDW WGs are comparable to losses of photolithographic multi-mode (0.04 dB/cm @ 850 nm) and single mode (0.59 dB/cm @ 1310 nm) WG builds. LDW multi-mode and single mode WG radial bend and crossing losses are evaluated for advanced optical communication channel routing capabilities and do not exhibit significant deviations from photolithographic-manufactured WG device loss.

Keywords: Polymer waveguides; Laser writing; Optical interconnects

1. Introduction

There is strong demand to utilize optical waveguides (WGs) to increase transmission speeds in bandwidth-limited electrical circuits, including servers and supercomputers [1–3]. Polymer WGs have been traditionally fabricated using the photolithographic process [4,5]. High resolution UV photolithography of WGs becomes increasingly difficult and expensive for large scale (>30 cm) multilayer optical-electrical printed wiring boards and backplanes.

An alternative method to fabricating WGs on large substrates is the laser direct writing (LDW) method [6,7]. LDW allows for the flexible fabrication of WGs through the use of a UV writing beam mounted on an XYZ movement stage. The focused UV beam is then scanned along the core material to selectively initiate polymerization within the core layer, as shown in Fig. 1. The LDW process presents a non-contact fabrication method of curing UV optical polymers at writing heights greater than 1 cm.

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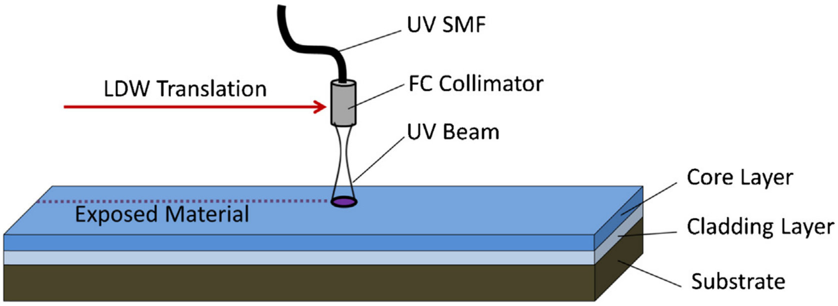

Fig. 1. Schematic of the LDW process.

This process exhibits excellent accuracy, flexibility, and scalability without incurring the high of costs of high-resolution photolithographic masks, making the LDW method cost-efficient and appealing for WG prototyping [8].

Previous LDW theoretical curing profile models [9,10] are not compatible with modern polymer WG materials due to unique proprietary chemical properties and curing kinetics. A new theoretical prediction model is developed to effectively correlate writing parameters with WG dimensions. The theoretical model incorporates Dow Corning Elastomers and similar materials for effectively performing LDW. A high-precision motion platform with an optimized UV source paired with the high-sensitivity optical elastomer makes this process to the best of the author's knowledge the fastest, most accurate LDW procedure for the fabrication of WGs with rectangular cross-section profiles [4,9,11].

A laser direct writing (LDW) method for fabricating single mode and multi-mode polymer WGs is presented. The fabrication steps with the mathematical formulations to correlate writing parameters to overall WG shape are presented. Theoretical calculations of WG widths are correlated with experimental results to show that the LDW process can be fine-tuned to obtain the desired WG dimensions. WG straights, bends, and crossings have been fabricated using the LDW method and their optical losses have been measured to show applicability for manufacturing.

2. Theoretical model

Waveguide dimensions fabricated through the LDW process are dependent on the spatial and temporal properties of the focused UV beam. The irradiance profile of the UV writing beam can be represented as a symmetric Gaussian beam [12], given by Eq. (1). P_t is the total output power and $W(z)$ is the width of the Gaussian writing beam that is dependent on the writing height, z.

$$I(\rho, z) = \frac{2P_t}{\pi W^2(z)} \exp\left[-\frac{2\rho^2}{W^2(z)}\right], \quad \rho = \sqrt{x^2 + y^2} \tag{1}$$

The material will experience an irradiance curing profile during the LDW process consistent with a Gaussian curve along the axis normal to the direction of propagation. This irradiance profile is obtained by taking the marginal probability distribution function (PDF) of Eq. (1). Multiplying the PDF by the dwell time, t_d, results in Eq. (2), the final energy curing profile of the LDW process. The dwell time is proportional to the diameter of the curing profile divided by the writing speed.

$$E(x, z) = \frac{\sqrt{2}P_t t_d}{\sqrt{\pi}W(z)} \exp\left[-\frac{2x^2}{W^2(z)}\right] \tag{2}$$

The WG polymer requires a minimum level of UV energy to initiate polymerization before thermal curing to solidify the material, making it resistant to solvent washing. Increasing the amount of UV exposure present during the writing process increases the region in the Gaussian curing profile that overcomes the energy threshold. This results in larger regions of polymer that will undergo solidification and form wider WGs.

By manipulating Eq. (2) and setting $E(x, z) = E_{thresh}$, the threshold energy required to initiate solidification, we can show that the width of the WG increases logarithmically in respect to higher total output power and longer dwell time. This correlation is given by Eq. (3).

$$WG\ Width = 2W(z)\sqrt{-\frac{1}{2}\ln\left(\frac{E_{thresh}\sqrt{\pi}W(z)}{\sqrt{2}P_t t_{dwell}}\right)} \tag{3}$$

In previous articles, LDW WGs exhibited Gaussian cross-sections due to the polymerization kinetics of the material in response to the Gaussian writing profile with polymerization rates proportional to the square root of the output intensity [9,10]. In comparison, the proposed model predicts only the width of the LDW WGs of