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Flexible multilayer substrate based optical waveguides: Applications to optical sensing

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ABSTRACT

The performance of flexible waveguides based microsystems such as optical waveguide sensors or a lab-on-a-chip platform is closely related to the parameters of the waveguides and substrates. In order to achieve enhanced performance of microsystems, we proposed a concept of flexible multilayer substrate based waveguides. We show that the mechanism properties of the flexible substrates and waveguides including the Young's modulus and the structural thickness can be well engineered and regulated by ranging the configuration of the multilayers with different materials. The multilayer substrate itself can also serve as a thin-film optical waveguide. The experimental results show that this structure is suitable for developing optical sensor chips like double-ring resonator based accelerometers. As an example, the theoretical analysis based on the tunable Young's modulus and thickness of the waveguides also provides an approach to achieve manufacturing error insensitive or accelerometer chips with different sensitivities between 10 per g and 53 per g. The sensitivity will be tenfold if propagation loss of the waveguides is reduced from 1.9 dB/cm to 0.3 dB/cm. This tunable structure promises to meet the requirements of various sensors and lab-on-a-chip systems for displacement, chemistry or biology measurements.

1. Introduction

The realization of miniaturized systems, such as micro-opto-electro-mechanical systems (MOMES) and lab-on-a-chip systems, offers potential for achieving more functional, more compact and higher-performance devices [1–3]. Flexible optical waveguides, due to their important roles in these systems, have continued to attract attention of scientists and enterprisers. A wide variety of flexible optical waveguide based systems have recently been demonstrated [4–12]. Among them, an integrated optical gas [6,7], displacement [8], force [9,10] or inertial [11,12] sensor chip specifically require high quality flexible optical waveguides. Their performance is closely related to the optical and mechanical parameters of the waveguides and substrates [6–16,25]. For example, low propagation loss, suitable Young's modulus from GPa to MPa levels and thickness below several hundred micrometers of the waveguides and substrates (which served as cantilevers) are the key parameters to achieve ideal cantilever-based sensor chips for integrated optical read-out [6,7] or accelerometer sensing [11,12] applications. However, few reports specifically discuss engineering and regulating these parameters of the substrate for integrated optical sensor chips. In this paper, we proposed a concept of compatible and adjustable flexible multilayer substrate based optical waveguide for flexible optical sensing applications. Propagation loss dependence of bending radius of the waveguides is demonstrated. The Young's modulus of the substrates is precisely controlled by varying the substrate thickness. Due to its unique structure, the substrate itself can also serve as a thin-film waveguide and promise further applications like integrated optical read-out systems [6,7]. Also, an innovative fabrication procedure is presented to fabricate flexible waveguides with bracing structures for the cantilevers. As an example, further theoretical calculations demonstrate their utility in optical acceleration sensing applications which shows capability for manufacturing error insensitive or high sensitivity accelerometers.

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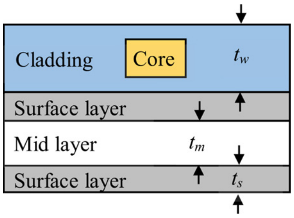

Fig. 1. Structure of multilayer polymer substrate based optical waveguides.

2. Design and fabrication

Since the performance of cantilever-based sensor chips is heavily dependent on the Young's modulus E and thickness t of the cantilever, it is of great important to fabricate high quality flexible substrates with controllable Young's modulus and thickness by choosing suitable polymer materials and the thickness of the multilayers of the substrates. Hence, we propose a concept of multilayer substrate to meet this requirement and here we used a 3-layer substrate to illustrate this concept. Fig. 1 shows the structure of a 3-layer substrate based waveguide. The substrate has a symmetrical configuration which consists of double surface layers and a mid layer. The total film thickness, or cantilever thickness t can be expressed as

$$t = 2t_s + t_m + t_w, \tag{1}$$

where t_s, t_m and t_w are the thickness of the surface layers, mid layer and cladding of the waveguide, respectively. The equivalent Young's modulus of the multilayers E can be express as follows:

$$E = \frac{2E_s t_s + E_m t_m + E_w t_w}{2t_s + t_m + t_w} \tag{2}$$

where E_s, E_m and E_w are the Young's modulus of the surface layers, the mid layer and the cladding of the waveguide, respectively. By carefully controlling the thickness of these polymer layers, the Young's modulus of the structure is precisely adjusted.

A UV-curable resin, NOA61 (Norland Products Inc.) and a commercially available negative photoresist, SU-8 (Baisiyou Corporation, Nanjing) were used as the substrate materials. In order to achieve substrates with different Young's modulus, the thickness of the mid layer was varying between 7 μm and 37 μm under different spin speeds. Two configurations of structures were compared in our experiment. One is SU-8, NOA61 and SU-8 (SNS) structure from top to bottom, while the other is NOA61, SU-8, and NOA61 (NSN) structure.

Both the structures have similar fabrication procedure as shown in Fig. 2. Take the fabrication of a SNS structure for example. Firstly, two scratches were made on the glass slide wafer to make the wafer easy to be cut off. Then, a polyvinyl alcohol (PVA) sacrifice layer was spin-coated on the glass slide followed by a dry etching progress using another glass slide as a mask to remove the PVA at both ends outside the scratches. It can make firm adhesions between both ends of the flexible substrate and glass slide wafer. The mask was in perfect alignment with the scratches. After that, an 18 μm-thick SU-8 film was spin-coated and located on the PVA layer as surface layer. It was heated to 95 °C, cured by Ultraviolet (UV) and followed by another 95 °C bake. Then, a NOA61 film was spin-coated at a speed between 1000 rpm and 5000 rpm and cured by UV. Another 18 μm-thick SU-8 layer was spin coated and achieved the substrate of a SNS structure.

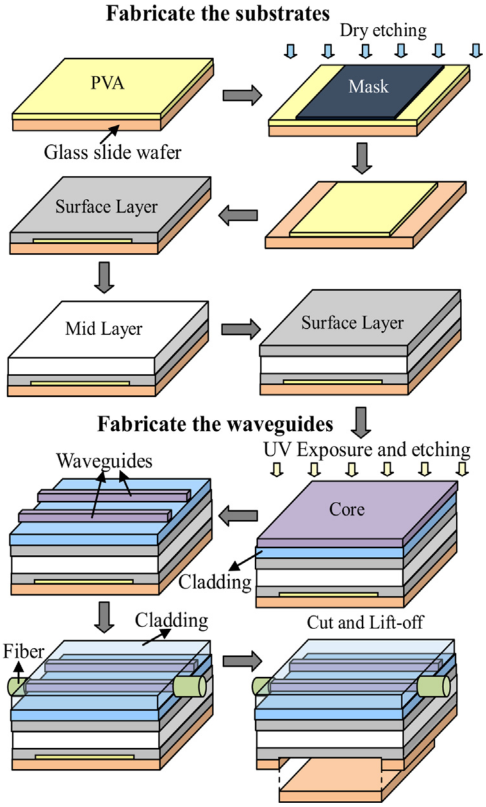

Fig. 2. Fabrication procedure of multilayer polymer substrate based waveguides with bracing structures.

Once the substrate is fabricated, a layer of NOA61 was spin coated on the substrate as the lower cladding. SU-8 2005 (Microchem Corporation) stripe core were fabricated by photolithography [24]. Then another layer of NOA61 was spin-coated and formed the upper cladding. After cutting off the glass slide wafer along the two scratches, the remaining glass slide slides can serve as the bracing structures of the cantilever-based sensor chips such as optical accelerometers mentioned in Ref. [12] and mounting pads for the coupling fibers. Separation of the device from glass wafer by dissolving the PVA layer in DI water completes the process.

3. Results and discussion

3.1. Characters of the substrates

One feature of the substrate is that it is able to serve as a planar optical waveguide. As Fig. 3(a) shows, light at a wavelength of 632.8 nm was coupled into the substrate by a prism coupler (SPA4000, Korea). Since there is a big difference between the refractive indexes of SU-8 (1.5909) and NOA61 (1.5578) at 632.8 nm, light propagated and was reflected in the substrate, Fig. 3(b) shows that light was reflected at one end of the substrate. Fig. 3(c) illustrates the propagation of light in a bent substrate without much bending loss. With this configuration, multilayer substrate provides further applications such as more compass, more functional and more cost effective guide-wave sensors and lab-on-a-chip systems for displacement, chemistry or biology measurements [6,7,19].

Young's modulus and thickness of SNS and NSN structures were measured by an electromechanical system (Intron 4466). Fig. 3(d) illustrates the relationship between Young's modulus and film thickness. It shows clearly that the Young's modulus decreases along with increasing film thickness for a SNS substrate, while it increases along with the increase of t for a NSN substrate. These plots show that both Young's modulus and film thickness are flexible with diverse multilayer configurations and different mid-layer polymers, which will strongly influence the sensitivity of an accelerometer.