Temperature-insensitive flexible polymer wavelength filter fabricated on polymer substrates

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Temperature-insensitive polymer wavelength filters with silicon nitride gratings were fabricated on a polymer substrate. Polymer waveguides on polymer substrates were fabricated on top of the Si wafer with a water soluble poly(vinylalcohol) (PVA) interlayer between the Si wafer and polymer waveguides. After the completion of the waveguides, the polymer waveguides are separated from the substrate by dissolving the PVA layer to form all polymer waveguides. The novel process provides a way to overcome the problem of the thermal instability of polymer substrate when the polymer waveguides are directly fabricated on polymer substrates. The polymeric wavelength filter fabricated on a polymer substrate exhibits one order of magnitude lower Bragg wavelength shift with temperature than the device on the Si-wafer in the temperature range of 25–70 °C, which is consistent with theoretical prediction. © *2005 American Institute of Physics*.
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Wavelength filters are essential components for the optical communication systems based on wavelength division multiplexing (WDM) in order to select one wavelength carrying a desired signal.[1,2] However the temperature dependence of the central wavelength of the reflected signal in the filters is a serious and outstanding problem for WDM systems. It is mostly caused by the temperature dependence of optical path length of devices.[3–7] Since this temperature sensitivity causes the crosstalk in the dense WDM systems with very small channel spacing, such narrow-band optical filters have required a precise temperature control unit. These problems can be solved by fabricating athermal (temperature-insensitive) waveguides.[3–7]

The Bragg wavelength, λ_0 is expressed as follows:

$$\lambda_0 = 2\Lambda_g N_{\mathrm{eff}}, \quad (1)$$

where N_{eff} is the effective refractive index of the guided mode in the filter and Λ_g is the grating period.[2] The temperature dependence of the central wavelength of filters is expressed by[8]

$$\frac{d\lambda_0}{dT} = 2\left(N_{\mathrm{eff}}\frac{d\Lambda_g}{dT} + \Lambda_g\frac{dN_{\mathrm{eff}}}{dT}\right) \quad (2)$$

$$= 2\Lambda_g\left(N_{\mathrm{eff}}\frac{1}{\Lambda_g}\frac{d\Lambda_g}{dT} + \frac{dN_{\mathrm{eff}}}{dT}\right). \quad (3)$$

Thus, $d\lambda_0/dT$ is given by the following equation:

$$\frac{d\lambda_0}{dT} = 2\Lambda_g\left(N_{\mathrm{eff}}\alpha_{\mathrm{sub}} + \frac{dN_{\mathrm{eff}}}{dT}\right), \quad (4)$$

where dN_{eff}/dT is the thermo-optic (TO) coefficient of the waveguide, and $\alpha_{\mathrm{sub}}(=1/\Lambda_g \cdot d\Lambda_g/dT)$ is the coefficient of thermal expansion (CTE) of the substrate. Since the substrate is usually much thicker than that of the waveguide layer, the coefficient of thermal expansion is determined by the substrate.[3] The athermal wavelength filter which shows no temperature dependence of the central wavelength of the reflected light can be realized by properly selecting the substrate and waveguide material to satisfy the following condition:

$$N_{\mathrm{eff}}\alpha_{\mathrm{sub}} = \frac{dN_{\mathrm{eff}}}{dT} = 0. \quad (5)$$

One needs to notice that it is not possible to realize athermal filters using silica based waveguides because α_{sub} (2.63 ppm for silicon wafer) and dN_{eff}/dT ($\approx +10^{-6}\ {}^\circ\mathrm{C}^{-1}$ for silica) are both positive so that $d\lambda_0/dT$ is always positive. In contrast, polymer waveguides allow achieving athermal devices by choosing a suitable combination of substrate and waveguide material with a negative TO value.

One difficulty of the fabrication of polymer waveguides on polymer substrates is the thermal instability of the substrates. Polymer waveguides are formed by spin coating of polymer solution followed by baking at elevated temperature to dry out the solvent. The baking process induces bending and shrinking of the substrates to make the process almost impossible.

In this paper, we report on temperature-insensitive wavelength filters using a new process to fabricate the devices on a polymer substrate. In the process, polymer waveguides are fabricated on a silicon wafer with a water soluble interlayer, poly(vinylalcohol) (PVA), between the waveguides and the substrate. A thick polymer layer, which was deposited on top of the waveguides by the doctor blade technique, is used as the substrate. Dissolving out the interlayer completes the polymer waveguide devices on the polymer substrate. The

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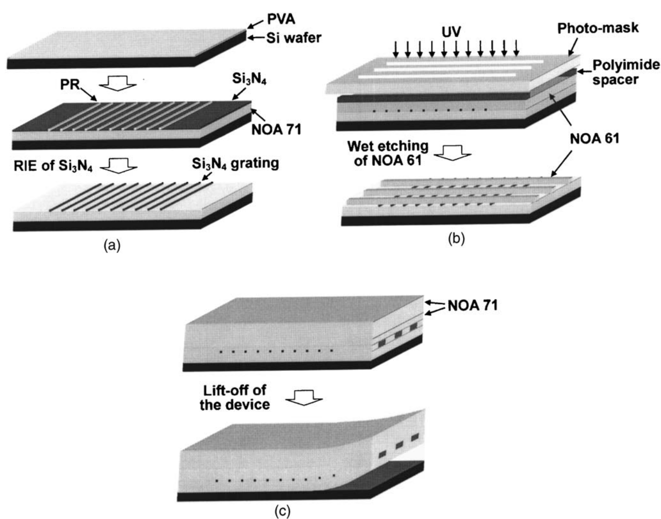

FIG. 1. Schematic diagram of the flexible wavelength filter on polymer substrate. (a) The transfer of PR grating as an etching mask to the Si_3N_4 layer by O_2 and CF_4 RIE, (b) the fabrication of channel waveguide using the proximate-contact lithography, and (c) lift-off of the device from Si wafer by dissolving the PVA layer in DI water after spin-coating of the NOA71 as the upper cladding and substrate.

process was applied to fabricate a temperature-insensitive wavelength filter.

Figure 1 shows the schematic diagram of the fabrication of the flexible polymer wavelength filter on a polymer substrate. UV-curable resins, NOA61 (Norland Products Inc. and $n^{\mathrm{TE}}=1.547$ at 1550 nm wavelength) and NOA71 (Norland Products Inc. and $n^{\mathrm{TE}}=1.540$ at 1550 nm wavelength), were used as the core and cladding materials, respectively. NOA71 was also used as the polymer substrate. After successive spin-coating and baking of 15-μm-thick PVA and NOA71 on the Si wafer, a 50-nm-thick silicon nitride (Si_3N_4) layer was deposited by plasma enhanced chemical vapor deposition. The Bragg gratings were fabricated by the holographic interference method using a photoresist (PR) and Ar^+ laser of 488 nm wavelength.[9] The PR gratings were transferred onto the Si_3N_4 layer ($n=1.8$) by using O_2 and CF_4 reactive ion etching (RIE) to induce a large difference of effective index between the grating layer and the core layer of the waveguide [Fig. 1(a)]. The period and depth of the transferred gratings were 495 nm and 50 nm, respectively. 3.5-μm-thick NOA61 layer was spin coated on the Si_3N_4 grating and the waveguide patterns were formed by proximate-contact lithography using negative-photomask attached to 25-μm-thick polyimide spacers followed by wet chemical etching of the unexposed area [Fig. 1(b)].[10,11] After spin coating and curing of the upper cladding layer (NOA71, 10 μm thick), 1.5-mm-thick NOA71 was coated as the polymer substrate by the doctor blade technique on the device. The NOA71 substrate was cured by UV with the intensity of 100 $\mathrm{mW/cm^2}$ for 25 min. Separation of the device from Si-wafer by dissolving the PVA layer in DI water completes the process [Fig. 1(c)].

Figure 2 shows waveguide patterns fabricated on the Si_3N_4 grating and the picture of the fabricated waveguide devices. The grating has a uniform period of 495 nm and a depth of 50 nm. These results indicate that the grating has been successfully fabricated by the process. The waveguide is well defined and has smooth side walls.

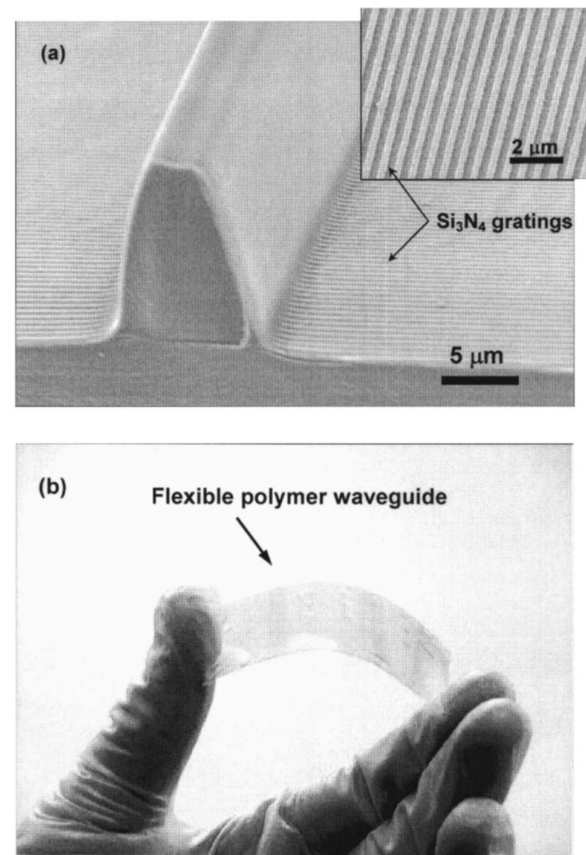

FIG. 2. (a) SEM image of the channel waveguide pattern fabricated by proximate-contact lithography on Si_3N_4 gratings defined by O_2 and CF_4 RIE, and (b) picture of the flexible wavelength filter fabricated on polymer substrate.

In order to measure the Bragg reflections of the device, a tunable laser source (HP81642A) operating around 1550 nm or broadband light source (HP83437A) covering the wavelength from 1100 nm to 1700 nm was used as an input light source through the single mode fiber. The output of the device was also launched to a single mode fiber and the output light was monitored with an optical power sensor (HP81635A) or an optical spectrum analyzer (HP86140B). The length of the device containing 10-mm-long Bragg grating was 3 cm. The polarization of the input light was adjusted to TE polarization using a polarization controller throughout the measurement.

The temperature dependence of the Bragg wavelength ($d\lambda_0/dT$) was measured in the temperature range between 25 and 70 °C by placing the waveguide on a temperature controllable waveguide holder (Suruga Seiki F274-18). Figures 3(a) and 3(b) exhibit the shifts of the transmission spectra of the optical filter when the temperature was increased from 25 to 70 °C, and the temperature dependence of the Bragg wavelength of the filters with the temperature sensitivity (slope) of −0.021 nm/°C, respectively.

The experimentally obtained $d\lambda_0/dT$ was compared with theoretically estimated values using the Eq. (4). We measured TO coefficient of NOA61 at the wavelength of 1550 nm by using the prism coupler with a hot stage to control the temperature of the film. The measured TO coefficient (dn/dT) was $-2.46\times10^{-4}\ {}^\circ\mathrm{C}^{-1}$ and the calculated dN_{eff}/dT using the beam propagation software (BeamPROP™, RSoft Design Group) was $-2.38\times10^{-4}\ {}^\circ\mathrm{C}^{-1}$ for TE polarization at

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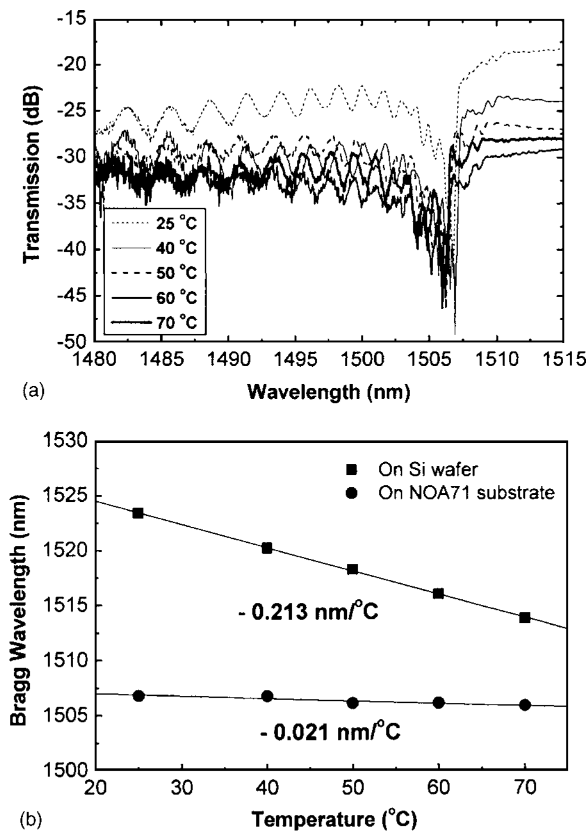

FIG. 3. (a) Transmission spectra of the Bragg grating filter fabricated on NOA71 substrate at different temperature, and (b) temperature dependence of the Bragg wavelength of the filter fabricated on Si wafer and NOA71 substrate, respectively.

1550 nm wavelength. The CTE value of NOA71 substrate was measured by TMA (Thermal Mechanical Analyzer, SEIKO TMA120). Figure 4 shows the displacement changes of NOA71 material with temperature in TMA measurements. The dimension of the sample for the measurement was $10\times10\times1.5$ mm^3. The sample was measured with the heating rate of 5 °C/min and the load of 20 g. The measured CTE value of the NOA71 polymer from the slope in the figure was 142.5 ppm/°C. The effective refractive index of 6×3.5 μm^2 (width$\times$height) waveguide with 50-nm-thick Si_3N_4 gratings is 1.5422 calculated using BeamPROP™. Therefore, the calculated temperature dependence of the wavelength shift ($d\lambda_0/dT$) of the polymer wavelength filter is −0.018 nm/°C, which is in good agreement with the experimental result of −0.021 nm/°C.

The temperature dependence of the Bragg wavelength of the filters fabricated on the Si-wafer is compared with the device on the polymer substrate in Fig. 3(b). The device exhibits a large shift of the Bragg wavelength from 1524 to 1514 nm as the temperature increases from 25 to 70 °C with the temperature sensitivity of −0.213 nm/°C. The temperature sensitivity of the Bragg wavelength was reduced by one order of magnitude when a device was fabricated on the NOA71 substrate replacing the Si wafer.

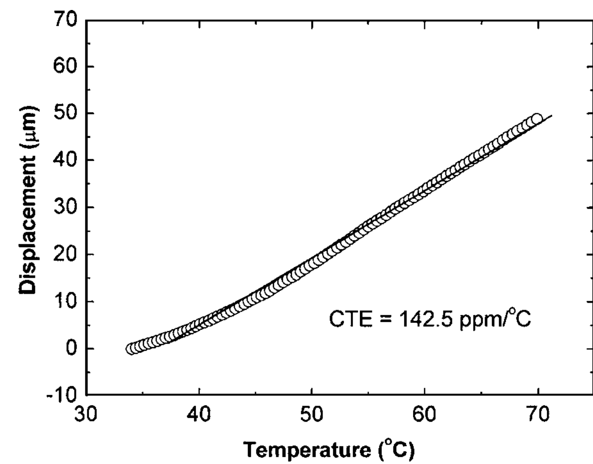

FIG. 4. Displacement changes of NOA71 material with temperature measured by TMA measurements.

In summary, temperature-insensitive polymer wavelength filters with Si_3N_4 gratings were fabricated on a polymer substrate. Polymer waveguides on polymer substrates were fabricated on top of the Si wafer with a water soluble PVA interlayer between the Si wafer and polymer waveguides. After the completion of the waveguides, the polymer waveguides are separated by dissolving the PVA layer from the substrate to form all polymer waveguides. The novel process provides a way to overcome the problem of the thermal instability of the polymer substrate when the polymer waveguides are directly fabricated on polymer substrates. UV-curable NOA61 was used as the core layer and NOA71 as the cladding and the substrate, respectively. The polymeric wavelength filter fabricated on a NOA71 substrate exhibits one order of magnitude lower Bragg wavelength shift with temperature than on the Si wafer in the temperature range of 25–70 °C, which is consistent with the theoretical prediction.

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