# Continuously tunable compact lasers based on thermo-optic polymer waveguides with Bragg gratings

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**Abstract:** Based on the thermo-optic tuning of a polymer waveguide Bragg reflector, we demonstrated a cost-effective tunable wavelength laser for WDM optical communications. The excellent thermo-optic effect of the polymer waveguide enabled direct tuning of the Bragg reflection wavelength by controlling the electrical power on a micro-heater. Wavelength tuning for 32 channels with 0.8 nm wavelength spacing was demonstrated as well as a continuous tuning with wavelength steps of 0.1 nm. To be qualified as a tunable laser for WDM-PON applications, wavelength stability within 0.15 nm was confirmed for an operating temperature range from -10 to 70 °C.



**OCIS codes:** (130.5460) Polymer waveguides, (3600) Tunable lasers, (1480) Bragg reflectors, (3120) Integrated optics devices.

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## 1. Introduction

Compact tunable lasers with a wide wavelength tuning range are of considerable interest for optical communications and sensor applications. In wavelength division multiplexed (WDM) optical communication systems, if a tunable laser is available at a reasonable cost, it could replace the fixed frequency distributed feedback (DFB) laser because the tunable laser resolves constraints of manufacturing and inventoring a series of light source cards with different wavelength codes [1]. The tunable laser is an indispensible component enabling a reconfigurable optical-add-drop multiplexing (ROADM) system where the data, carried by a certain wavelength, is extracted from the multiplexed optical signal and then replaced by other data. The recent deployment of WDM-PON system demonstrating much wider bandwidth than other competing PON systems makes strong demands on compact tunable lasers that could be easily fabricated in mass production. Moreover, cost-effective tunable lasers would be highly useful for wavelength interrogation in optical sensors monitoring the change of a reflection spectrum [2]. Tunable lasers have also been incorporated in optical coherence tomography for improving image quality [3].

There have been various approaches in demonstrating tunable lasers especially for WDM applications. Wide tuning range was accomplished by incorporating an acousto-optic tunable filter in $LiNbO_3$ [4], a coupled ring resonator in a silica waveguide [5], an additive Vernier effect by relative tuning of two modulated gratings [6], and a silicon waveguide grating router with a thermo-optic phase shifter [7]. In addition to wavelength tuning, to prevent channel crosstalk during wavelength switching, a tunable laser integrated with a variable optical attenuator was also demonstrated [8].

In order to obtain a cost-effective solution, in this work, a polymeric waveguide Bragg reflector with a thermo-optic (TO) tuning capability was incorporated for providing external feedback of a certain wavelength into a superluminescent diode (SLD) with a broad gain spectrum. A polymer waveguide has merits of a large thermo-optic effect as well as good efficiency for heat insulation resulting in large refractive index tuning for small power consumption. Hence, the direct tuning of a Bragg reflector, requiring a large index change, is viable in a polymer waveguide just by applying heat on a simple grating structure [9]. In the case of a semiconductor device, refractive index tuning is not enough to introduce sufficient wavelength tuning in a Bragg reflector. Consequently, a sampled grating had to be incorporated to extend the tuning range based on the Vernier effect [10]. By the way, the polymer waveguide device has a large potential for low-cost manufacturing in terms of the nano-imprinting fabrication process [11]. A flexible polymer grating device would be useful in extending the wavelength tuning capability beyond the limits of the thermo-optic effect [12].

Compared to previous work based on polymer waveguide platforms [13], in this work, we demonstrated a hybrid package of a SLD and a polymer Bragg reflector in order to resolve the complicated packaging issue. Due to the enhanced reliability of the polymer device, hermetic package was required only for the semiconductor light source chip. The phase modulation device of previous work became obsolete with this hybrid packaged device in terms of the reflection property optimization of the polymer Bragg reflector. Wavelength stability within the requirement for WDM-PON was demonstrated by incorporating feedback control of the substrate temperature.

## 2. Design and fabrication

The tunable laser proposed in this work, as depicted in Fig. 1, consists of a polymer waveguide device integrated with a Bragg reflector, a SLD light source, and an aspherical microlens between the two components. TO can type hermetically packaged SLD was used [14]. Due to the improved stability, polymer waveguide device could be operated in air with no need of costly hermetic packaging [15]. The source light emitting from a mode size converted waveguide was coupled to a polymer waveguide through an aspherical microlens. By applying a current on the integrated heater of the polymer device, the reflection wavelength of the Bragg reflector was controlled, which determined the lasing frequency of the tunable laser.

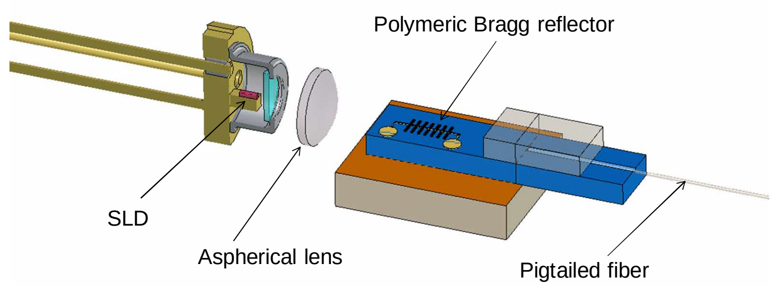


Fig. 1. A schematic diagram of the proposed hybrid packaged tunable laser consisting of a SLD, an aspheric microlens, and a polymeric tunable Bragg reflector.

The low-loss polymer, used for the waveguide grating, was a highly fluorinated acrylate material, the LFR, with a minimum absorption loss at 1550 nm and low birefringence in a crosslinked thin film. The basic chemical structure of the LFR is illustrated in the inset of Fig. 2. By fabricating a planar waveguide on a silicon substrate with two layers of LFR polymers, we measured the propagation loss of the material in terms of a liquid immersion prism coupling technique. Because the polymer had very low loss, it was hard to obtain clear data with this measurement. After repeated measurements, as shown in Fig. 2(a), we concluded that the polymer waveguide had a propagation loss of less than 0.1 dB/cm at 1550 nm. The wavelength tuning property of the Bragg reflector was associated with the thermo-optic effect of the polymer material. Fig. 2(b) shows the refractive index of the polymer material as a function of temperature, which corresponds to a TO coefficient of $-2.567 \times 10^{-4}$ /°C and $-2.476 \times 10^{-4}$ /°C for TE and TM polarizations, respectively. From the measured TO coefficient, to obtain wavelength tuning for 32 channels with 0.8 nm spacing, the temperature at the waveguide core has to be increased by 87 °C.

Without incorporating additional high index material, through the modulation of core thickness, one can obtain sufficient grating reflectivity for the external feedback. Effective index change of the fundamental guided mode due to the core thickness variation was calculated. Then, by a transmission matrix calculation, we obtained the reflectivity of Bragg grating with a length of 2 mm as shown in Fig. 3. For a waveguide core of 6 x 6 $\mu m^2$ and a refractive index of 1.38, more than 50% of the reflection could be achieved for a waveguide contrast of 0.01 and an etch depth of 400 nm. A higher contrast results in a stronger reflection for a given etch depth. For the purpose of external feedback in a cavity, a strong reflection was detrimental causing multimode lasing and output power fluctuation.

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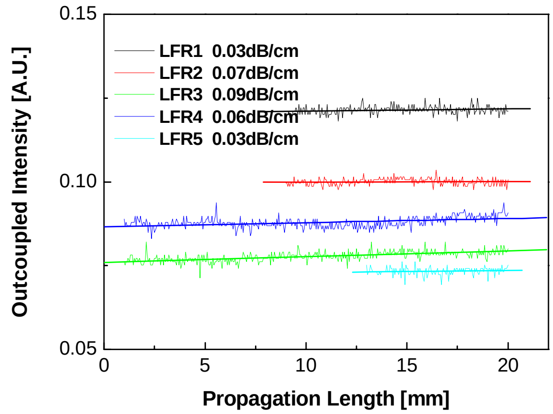
(a)




(b)

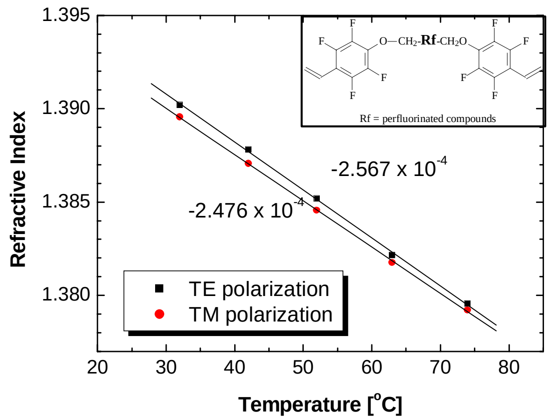



Fig. 2. The optical properties of LFR polymers: (a) propagation loss measured by a liquid immersion prism coupling technique from a planar waveguide consisting of two layers of LFR polymers, and (b) thermo-optic property of the LFR polymer measured for both TE and TM polarizations. The inset shows the basic chemical structure of the LFR polymer.

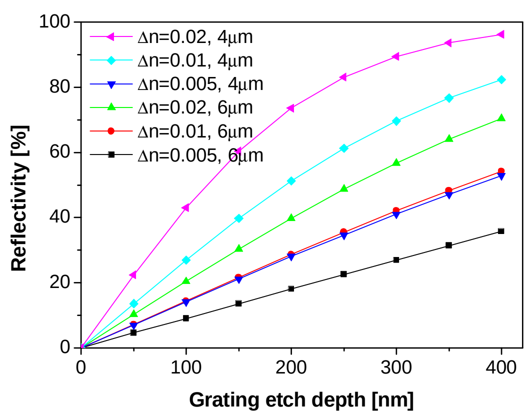



Fig. 3. The reflectivity of a 2-mm long polymer waveguide Bragg reflector calculated as a function of the grating etching depth for various waveguide contrasts.

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Polymeric Bragg reflector was fabricated by conventional process steps shown in Fig. 4. The waveguide structure was formed by spin coating and UV-curing of the two LFR polymers producing an index contrast of 0.01. The waveguide core was defined by photolithography using a silicon photoresist and by dry etching in oxygen plasma. Surface relief Bragg grating was fabricated on top of the waveguide core layer. Because polymer materials have the lower refractive index than semiconductors, the polymer Bragg reflector needs the longer grating period, and then the fabrication tolerance becomes much wider. For fabricating first order grating with a period of about 562 nm, a laser interference lithography with a 488 nm He-Cd laser was incorporated [12]. Other method to fabricate the grating using a nano-imprinting or direct photolithography is currently under investigation to be incorporated on next version of device. After the upper cladding coating, a metal heater was fabricated with an e-beam evaporation of Ti-Au and a conventional patterning process. A single mode fiber was pigtailed on one end of the polymer waveguide. The other end of waveguide was aligned to SLD along with a lens to achieve maximum output intensity. Then, it was fixed on the package in terms of a laser welding process. The coupling loss between the polymer waveguide and the gain chip with a output mode size converter was about 4.0 dB.

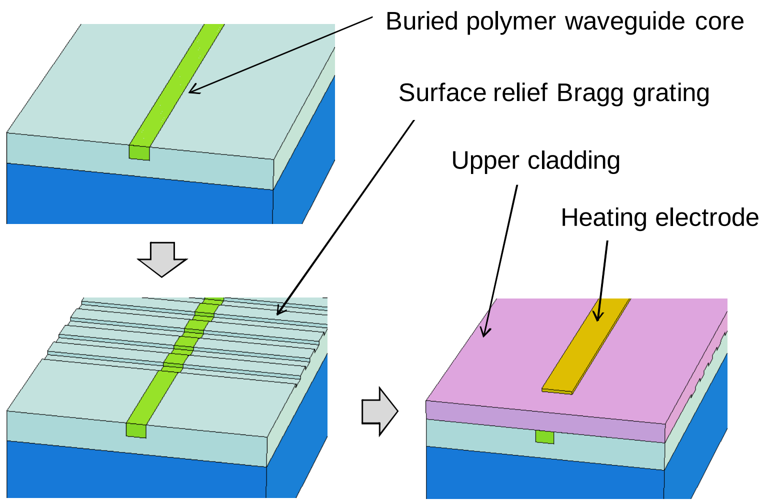


Fig. 4. The schematic fabrication procedure of the polymer waveguide Bragg reflector.

### 3. Characteristics of polymeric tunable laser

The typical transmission and reflection spectra of the polymer grating, before it was packaged, were measured as shown in Fig. 5. The initial transmission peak was located at a wavelength of 1562.6 nm with a loss of 5.0 dB. In the reflection spectrum measured using a circulator, a loss of about 1.5 dB was observed. The reflectivity of the polymer grating was about 70% in this sample which was higher than the target reflectivity of 50%. The 3-dB bandwidth of reflection peak was about 0.6 nm. Though there was considerable reflection by the side lobe, it has no effect on the lasing spectrum of the external cavity laser.

The lasing property of the packaged external cavity laser was evaluated by measuring the L-I curve as shown in Fig. 6. The packaged device was placed in an oven and the temperature was changed from 25 to 70 °C. During the measurement, the TEC under the gain chip was off, but the temperature of the Bragg reflector was maintained for wavelength locking. The slope efficiency of the laser was 0.105 W/A at 25 °C, and decreased to 0.065 W/A at 70 °C.

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The output power efficiency could be improved by employing a state of the art SLD chip that has become recently available commercially.

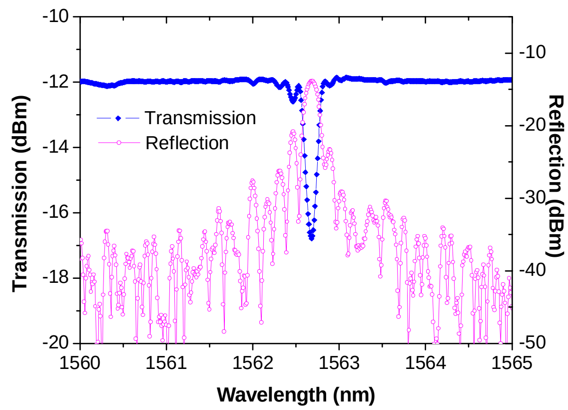


Fig. 5. The reflection and transmission spectra of the polymer waveguide Bragg reflector.

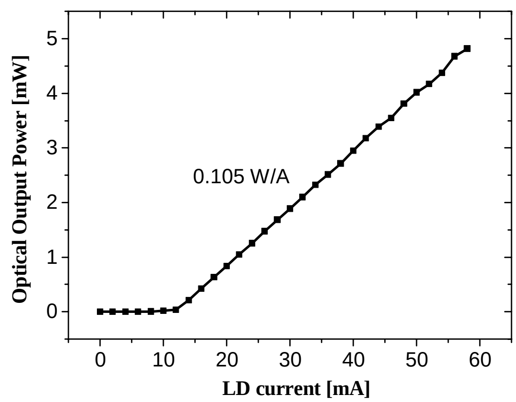


Fig. 6. The lasing behavior of a polymer waveguide tunable laser given by a L-I curve measured for different operating temperatures with no TEC control. The slope efficiency of the laser at 25 °C was 0.105 W/A.

Wavelength tuning characteristics were measured by applying electrical heating power on the micro-heater of the device. As shown in Fig. 7(a), the output wavelength was tuned to the 32 wavelength channels with a channel spacing of 0.8 nm by applying an electrical power of 150 mW for maximum tuning. For demonstrating continuous tuning of the lasing wavelength, as shown in Fig. 7(b), the device was tuned with a step size of 0.1 nm by the precise control of heating power. The output power of the tunable laser was set to 3 dBm. The power fluctuation during the tuning was negligible. The linewidth of the lasing spectrum was measured as 0.1 nm at 20 dB from the peak.

To be useful for a practical WDM passive optical network (PON), wavelength stability over an operating temperature range from -10 to 70 °C was investigated as shown in Fig. 8. In this measurement, TEC was operated to maintain the substrate temperature of both the gain chip and the polymer chip. As the temperature increased, the lasing wavelength continuously red shifted due to the refractive index increase of the micro-lens included in the cavity. Then, an abrupt change of wavelength for 0.06 nm occurred due to mode hopping in the laser cavity with a length of about 15 mm. The peak wavelength, just before the mode hop, increased by

0.09 nm until the oven temperature increased from -10 to 30 °C, then it started to decrease as the temperature raised to 70 °C. This effect happened due to a slight difference between the monitored temperature by using a thermocouple and the actual temperature on the polymer substrate. It could be further reduced by improving the temperature monitoring scheme. The overall variation of the lasing frequency was within 0.15 nm, which was sufficient to be qualified for WDM-PON applications.

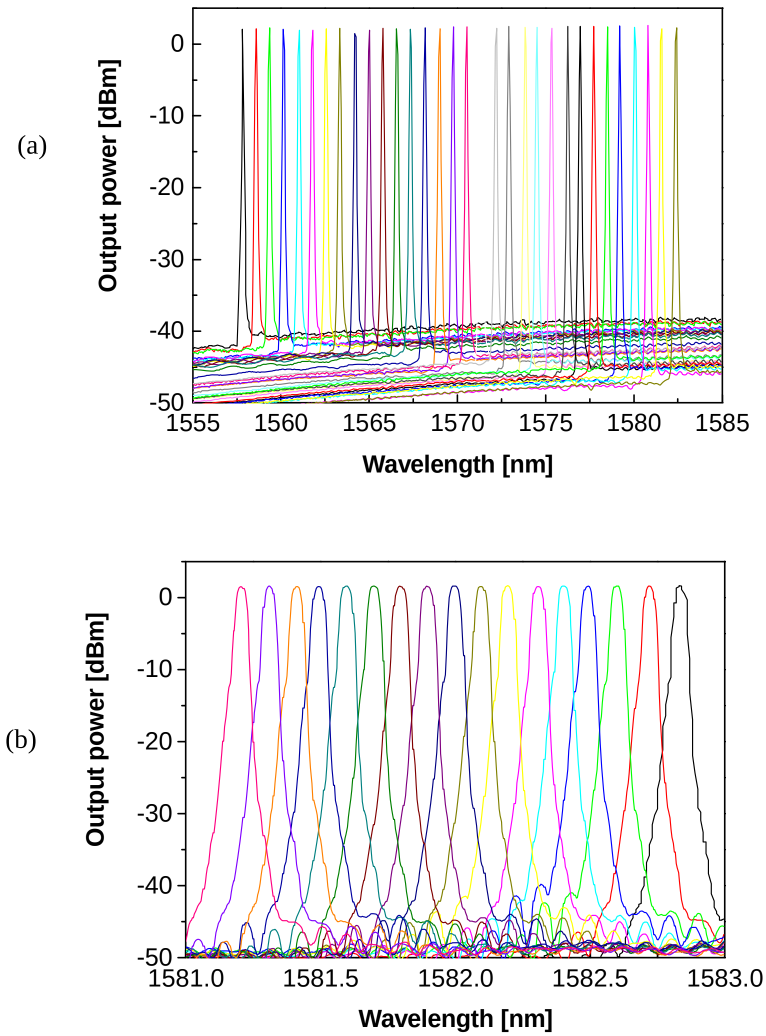


Fig. 7. The wavelength tuning characteristics of the polymer Bragg grating tunable laser: (a) wide tuning for 32 channels from 1557.8 nm to 1582.6 nm with a 0.8 nm wavelength step, and (b) continuous tuning for a narrow tuning range with a wavelength step of 0.1 nm.

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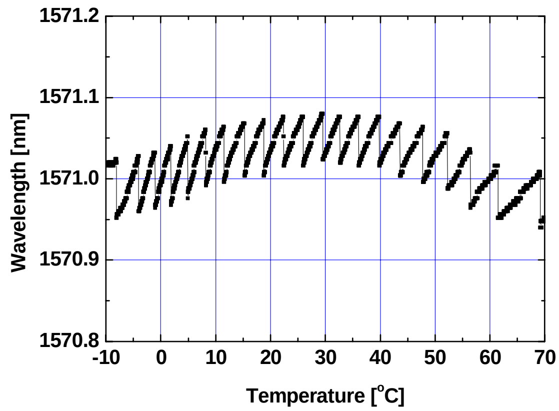


Fig. 8. Wavelength stability of the polymer grating tunable laser for an operating temperature ranging from -10 to 70 °C. The temperature of both the gain chip and the polymer device was maintained by the respective TECs, and then the total output wavelength variation was within 0.15 nm.

## 4. Conclusion

In conclusion, we demonstrated a tunable wavelength laser based on thermo-optic tuning of a Bragg reflecting polymer waveguide in order to provide a cost-effective solution for WDM optical communications. A SLD light source, packaged hermetically, was aligned to a polymer waveguide substrate through a micro-lens. The excellent thermo-optic effect of the polymer waveguide enabled direct tuning of the Bragg reflection wavelength by controlling the applied power on a micro-heater. The reflection property of the Bragg reflector was carefully adjusted to prevent output power fluctuations during wavelength tuning without the use of an additional phase modulator. Wavelength tuning for 32 channels with 0.8 nm wavelength spacing was demonstrated as well as continuous tuning with a wavelength step of 0.1 nm. To be qualified as a tunable laser for WDM-PON applications, wavelength stability within 0.15 nm was confirmed for an operating temperature range of -10 to 70 °C. The device is currently under the evaluation to be employed as a cost-effective tunable light source for 2.5 Gbps WDM-PON systems.

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