Flexible Polymeric Tunable Lasers for WDM Passive Optical Networks

Kyung-Jo Kim, Min-Cheol Oh, Sang-Rok Moon, and Chang-Hee Lee

***Abstract*—Flexible polymer waveguide with a Bragg reflection grating is incorporated to form an external cavity laser with a wide tuning range, and it is evaluated as a tunable light source for wavelength division multiplexing optical communication systems. The highly elastic property of polymer materials makes them suitable for producing a tunable Bragg reflector controlled by an imposed strain. The flexible tunable Bragg reflector is installed on a compact moving stage 6 connected to a piezoelectric motor. By applying a total strain of 60680 $\mu\varepsilon$ (6.07%), wavelength tuning of 82 nm is achieved with a side-mode suppression ratio of 43 dB and a linewidth less than 0.1 nm. The tunable laser controlled by a microactuator exhibits long-term stability with a wavelength fluctuation of less than 0.1 nm. In the optical transmission experiment, various wavelengths are used to transmit the 2.5 Gb/s signal over 50 km, excellent performance was observed with a power penalty of 1 dB compared to the DFB laser.**

***Index Terms*—Bragg reflectors, flexible polymer devices, polymer waveguides, tunable lasers.**

I. Introduction

TUNABLE lasers have now become a key component enabling the success of wavelength division multiplexing (WDM) passive optical networks (PONs) since the advent of low-cost solution of tunable light sources [1], [2]. To apply WDM technology to a low-cost PON network, light sources based on an injection locking method have been adopted [3]. When the length of the optical link increases, the amount of Rayleigh back-scattered light also increases, which interferes with the injection locking. The reflected signal cannot be simply rejected because it contains a seed light for the wavelength locking. This effect provides the practical limit of the service distance and bandwidth of the WDM-PON system based on injection locking method. Compared to the injection locking method, if the tunable laser is incorporated, there's no difficulty to remove the reflected signal, and then the WDM-PON system could provide a much longer transmission distance [4].

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Previously reported tunable lasers can be categorized as either monolithic or hybrid devices. To achieve a wide tuning range in a monolithic integrated device, a sampled grating structure was used to extend the tuning range [5], and arrayed lasers with different wavelengths were fabricated on a single chip along with a wavelength multiplexer [6]. In a hybrid-type laser, the gain section was separated from the wavelength tuning section to form an external cavity laser (ECL). A mechanically tuned ECL with a rotating grating was demonstrated with a fast tuning speed of 15 ms [7]. A thermally tunable ECL was demonstrated in a polymer waveguide grating device with a tuning range covering 32 wavelength channels with 0.8-nm spacing [8]. Although the hybrid device requires a larger footprint than the monolithic integrated device, it has a higher production yield because it uses simpler higher-yield components.

Among the various tunable laser technologies, the thermo-optic (TO) polymer ECL device has drawn considerable attention since it was recently adopted for a commercial WDM-PON system. The large TO coefficient and excellent heat insulation of polymers enable a refractive index change of more than 2.5% for a temperature change of 100°C. Hence, the Bragg reflection wavelength is widely tunable by using a simple microheater placed on the polymer waveguide. Another advantage of polymer devices is the convenient fabrication procedure, which consists of spin-coating the waveguide layers and oxygen plasma etching to define the waveguide structure. It does not require any toxic chemicals or high-temperature processes. Therefore, polymer devices can be produced in a conventional production facility at a competitive production cost.

By virtue of the unique properties of organic polymer materials, various novel approaches have been demonstrated. Through the doping of organic dye to produce an optical gain, a distributed feedback polymer laser with an imprinted grating was demonstrated [9]. A strain-induced tunable organic laser was also demonstrated by encapsulating a fluorescent organic material in a flexible polymer matrix [10]. The tuning range was widely extended over 80 nm by applying both compressive and tensile strain to an ECL incorporating a flexible polymeric Bragg reflector [11]. Furthermore, an electrically deformable elastomer combined with an electroactive polymer was investigated to demonstrate voltage-tunable elastomer lasers [12].

Although various unique polymeric tunable lasers have been demonstrated, so far the only technology close to commercial penetration is the thermally tunable ECL, in which the tuning range is limited by the heater reliability. In this work, we propose a strain-tunable polymeric ECL as a widely tunable cost-effective light source for WDM-PONs. By employing the ECL

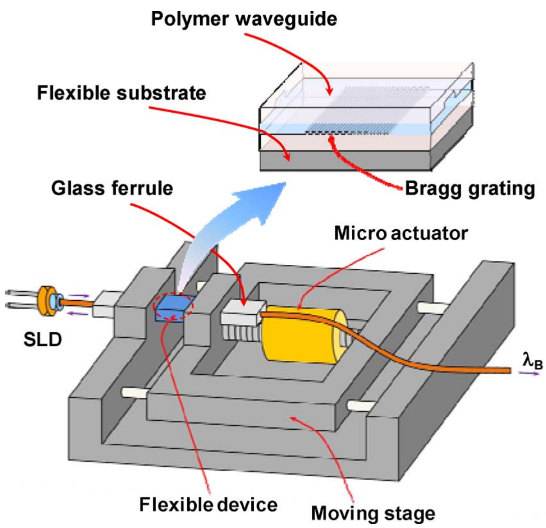

Fig. 1. Schematic diagram of strain-induced external cavity tunable laser consisting of a superluminescent laser diode (SLD) acting as a gain medium and the flexible Bragg reflector acting as a wavelength-selecting tunable reflector. The polymer waveguide flexible Bragg reflector is attached to a moving stage driven by a microactuator to form a compact device package.

and an external modulator, 2.5 Gb/s transmission over a distance of 50 km is demonstrated for various tunable wavelengths from 1510 nm to 1570 nm in order to verify that the device is suitable for WDM-PONs.

II. Flexible Polymer Waveguide Bragg Reflector

To construct ECL, the flexible Bragg reflector was connected to a super-luminescent laser diode (SLD) used as a gain medium, as shown in Fig. 1. The SLD had a high-reflection coating on one side and an antireflection coating on the other. To connect the Bragg reflector and the SLD, it was necessary to use a polarization-maintaining (PM) fiber to preserve the polarization during operation. Moreover, the length of the fiber should be minimized to increase the free spectral range so as to suppress other longitudinal modes.

Bragg reflectors in polymer waveguides have been demonstrated in the form of a surface relief grating and a volume index modulation grating [13], [14]. In the volume grating, the refractive index change induced by the grating-writing laser exposure is difficult to measure and changes depending on the polymer material. Hence, the surface relief grating has better reproducibility. In an earlier version of the surface relief grating, an additional high-index polymer layer was inserted as a grating element to obtain sufficient reflectivity. However, in our recent design, an increase in the index contrast between the core and the cladding polymers makes the high-index polymer grating obsolete, resulting in a simplified device structure.

The polymer materials selected for the core and cladding layer have refractive indices of 1.455 and 1.430, respectively, resulting in a contrast of 0.025 (1.7%). According to oversized rib waveguide design, one can find a single-mode waveguide structure even for a large refractive index contrast. The large contrast is beneficial for obtaining high reflectivity in the Bragg grating without increasing the etch depth of the submicron grating.

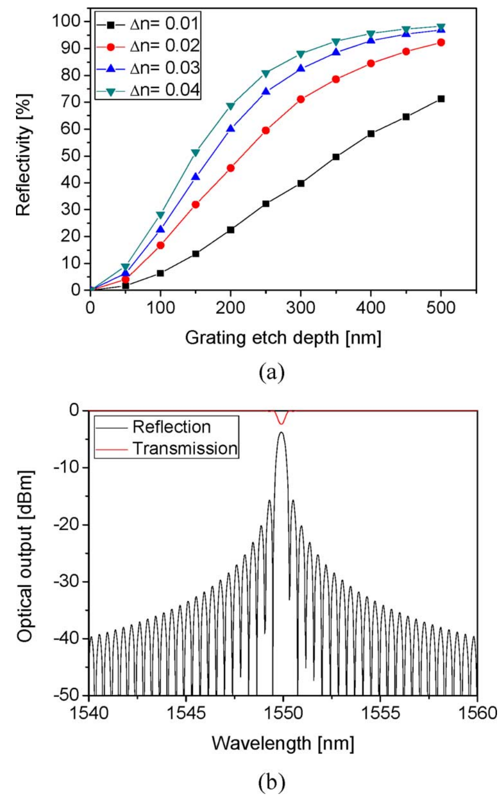

Fig. 2. Design results of the polymer waveguide Bragg grating device: (a) reflectivity of grating calculated as a function of grating etch depth for various index contrasts of the waveguide materials, and (b) reflection and transmission spectra for a grating with moderate reflectivity.

To design the Bragg reflector, the effective index modulation caused by the thickness change of the core layer was calculated, and then the reflectivity of the grating was obtained by the transmission matrix method. The reflectivity of the grating affects the spectral linewidth of the ECL, and a reflectivity of less than 50% is preferred for single longitudinal mode operation with a narrow linewidth. The reflectivity of the grating is calculated as a function of its etch depth, as shown in Fig. 2(a); for a given etch depth, the reflectivity increases as the refractive index contrast increases. For a waveguide with a core of 4×6 μm^2 and grating etch depth of 150 nm, the reflectivity becomes about 38%, and the reflection and transmission spectra were obtained, as shown in Fig. 2(b).

The fabrication procedure for the flexible Bragg reflector consists of three steps: flexible plastic substrate preparation, grating fabrication with laser interferometry, and waveguide fabrication and lift-off of the flexible device. Because the flexible substrate was too unstable for a fine grating structure to be formed on it, the device was built on a hard silicon wafer, and then the flexible device was lifted off at the end of the fabrication procedure. Before waveguide fabrication, a 100-μm-thick flexible polymer substrate layer was formed on the silicon wafer by spin-coating a UV-curable NOA61 polymer. Before the spin-coating, a Au metal layer was formed on the silicon wafer, and SU-8 polymer was coated with a thickness of less than 1 μm. SU-8 polymer has weak adhesion over Au but good adhesion on the silicon surface. Hence, one can define the areas to be lifted off by the

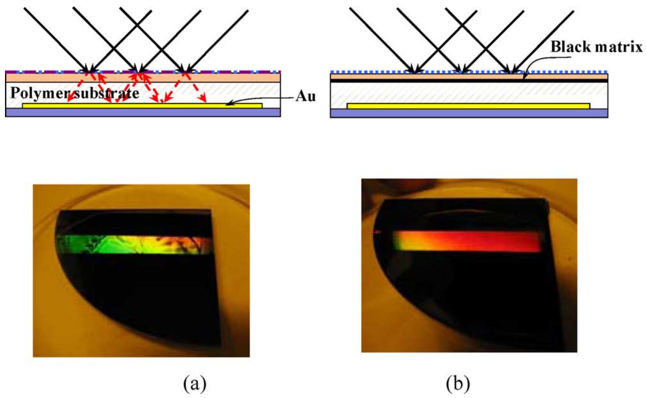

Fig. 3. Gratings fabricated by laser interferometry: (a) on a thick plastic layer coated on a Au-coated silicon wafer, resulting in unclear interference pattern and (b) highly uniform grating obtained by incorporating black matrix material to eliminate the undesired reflected beam.

Au pattern and apply the SU-8 and NOA61 films over the patterned Au substrate.

Over the thick polymer substrate layer, a lower cladding layer was formed by spin-coating ZPU polymer to a thickness of 10 μm. A laser interference pattern was exposed on a photoresist coated on the lower cladding layer to form a grating pattern, and the pattern was transferred to the lower cladding layer by oxygen plasma etching. During grating fabrication, the interference pattern became unclear, as shown in Fig. 3(a), because of interference between multiple reflected beams. The grating pattern was greatly enhanced, as shown in Fig. 3(b), by adopting a black matrix absorbing material under the lower cladding layer to absorb the undesired reflected beams [15].

The core layer of the waveguide was formed by spin-coating another ZPU polymer over the grating pattern. Then a waveguide pattern was defined by photolithography and oxygen plasma etching. The thickness of the core layer was 4 μm, the width of the waveguide was 6 μm, and the etch depth was 1.6 μm; these dimensions satisfy the single-mode condition in an oversized rib waveguide structure. The upper cladding layer was formed by spin-coating the ZPU polymer used for the lower cladding. To lift off the flexible part, the sample was diced to separate the part attached to the silicon wafer; then the film coated over the Au pattern was lifted off immediately. On the flexible polymer device, polydimethylsiloxane polymer blocks were attached to keep the polymer film from buckling during the compressive strain application. Additional glass blocks were also attached to the film for pigtailing the V-groove fiber blocks. A PM fiber was attached to one side of the sample, and a single-mode fiber was pigtailed on the other side.

III. Characteristics of Tunable External Cavity Laser With Flexible Bragg Reflector

Flexible device was attached to a moving stage and driven by a piezoelectric motor-type microactuator (Squiggle, Microscale Co.), as shown in Fig. 4. The Squiggle actuator has very tiny dimensions, as small as $2.5 \times 2.5 \times 10$ mm^3, and can produce a force of 2 N. The metal screw at the center of microactuator is rotating when a driving signal is applied, and then the moving stage is moved back and forth depending on the applied voltage.

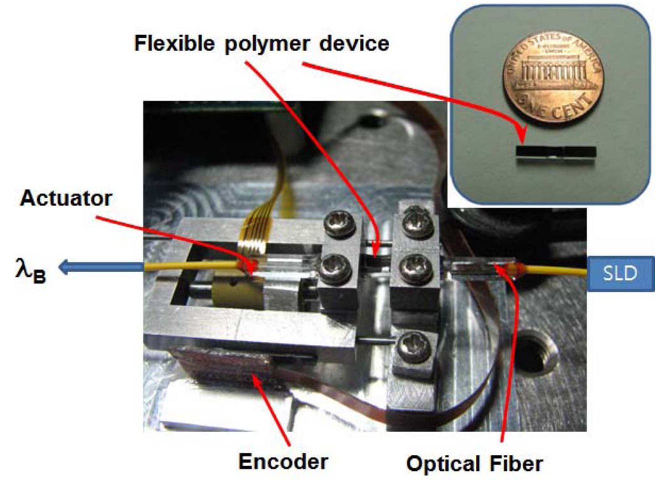

Fig. 4. Photograph of the flexible Bragg grating device attached to the Squiggle actuator. Inset compares the size of the flexible Bragg reflector to that of a US one cent piece.

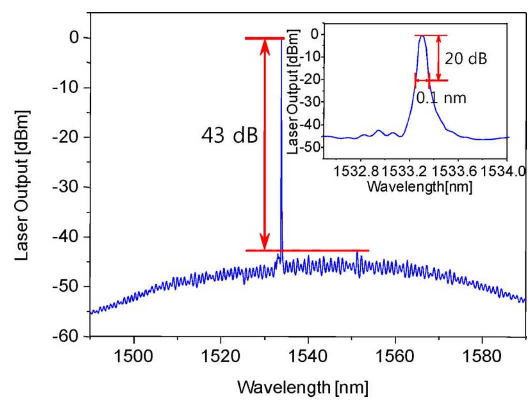

Fig. 5. Output spectrum of the ECL exhibiting an output power close to 0 dBm, an SMSR of 43 dB, and a 20-dB bandwidth of 0.1 nm.

It has an integrated magnetic encoder with a resolution of 0.5 μm, and its maximum travel distance is 7 mm. To obtain wavelength tuning of ± 50 μm by imposing compressive and tensile strains, stretching and compression of about 3.4% is thought to be necessary in the flexible polymer. Hence, the required displacement is less than 100 μm for a flexible device length of 3 mm. Although the elasticity depends on the polymer material, most polymers have good elasticity and can easily be stretched by more than 5%.

Before the strain was applied, the initial lasing spectrum was measured, as shown in Fig. 5. TE polarization was excited by adjusting the angle of the PM fiber between the SLD and the Bragg reflector. The SLD had a center wavelength of 1535 nm and a 3-dB bandwidth of 65 nm. The ECL's output spectrum exhibited a peak power of -0.5 dBm for a wavelength of 1536.1 nm, a side-mode suppression ratio (SMSR) of 43 dB, and a linewidth less than 0.1 nm at -20 dB, which was resolution limit of the spectrum analyzer.

In the wavelength tuning experiment, the microactuator was moved by 4.0 μm at each step because of the resolution limit of the encoder. For a flexible part length of 2.7 mm, the imposed strain corresponds to 1480 $\mu\varepsilon$ (0.148%), which was expected to induce a wavelength shift of 2.27 nm at each step. The sample

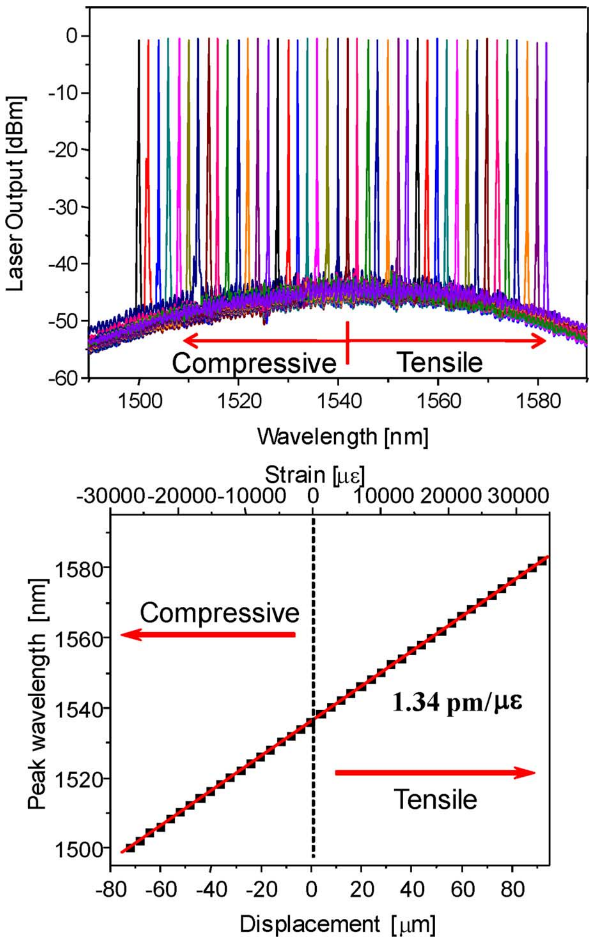

Fig. 6. Wavelength tuning characteristics of the polymer Bragg grating tunable laser.

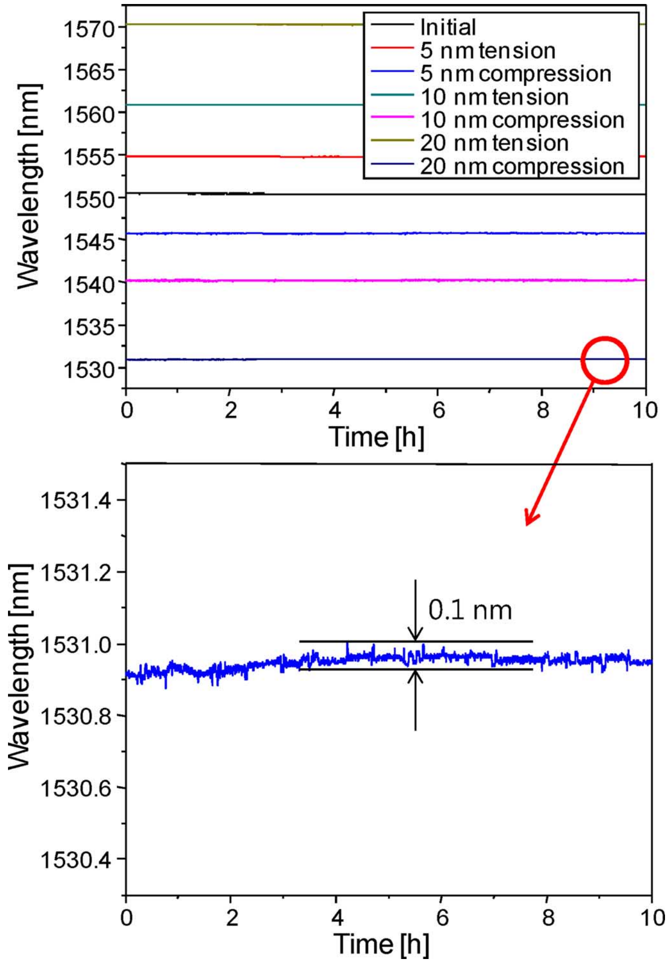

Fig. 7. Wavelength stability of the tunable lasers measured under various imposed strains.

with an initial wavelength of 1536.1 nm was compressed by 72 nm in 18 steps to impose the maximum compressive strain of 26640 $\mu\varepsilon$ (2.664%); the wavelength was blue-shifted by 36 nm (2.34%) to 1500.1 nm. When the sample was stretched by 92 μm in 23 steps, the imposed tensile strain was 34040 $\mu\varepsilon$ (3.404%), and a red shift of 46 nm (2.99%) to 1581.9 nm occurred. The discrepancy in the ratio of the wavelength shift to the imposed strain is explained by the strain-optic effect, and the strain-optic coefficient of the ZPU polymer was found to be 0.12 in this experiment.

Throughout the wavelength tuning experiment, as shown in Fig. 6, the tunable laser exhibited single-mode operation. Interestingly, despite the uneven gain spectrum of the SLD, the ECL produced almost equalized output power over the entire tuning range by virtue of the stimulated emission. The increase in wavelength as a function of the imposed strain is also drawn in Fig. 6. The wavelength shift was linearly proportional to the applied strain with a ratio of 1.34 pm/$\mu\varepsilon$. The linearity implies that the microactuator produced sufficient force and position accuracy by using the integrated encoder.

IV. 2.5 Gb/s Transmission Experiment Incorporating the Flexible Grating ECL

The wide tuning capability of the flexible polymeric ECL makes it attractive as a light source for WDM optical communication systems. The tuning range of the flexible polymer ECL covers the wavelength ranges of the C and L bands. Before the transmission experiment, the wavelength stability of the device was evaluated at various wavelengths to verify that it has sufficient reliability for long-term operation. As shown in Fig. 7, the device exhibited various initial wavelengths depending on the imposed strain, and then the imposed strain was maintained for 10 h in a laboratory with no specific temperature control. The magnified graph shows that the wavelength fluctuation was within 0.1 nm, which could provide sufficient stability for the WDM optical communication experiment. In this device, the wavelength stability was determined mainly by the accuracy of the microactuator's encoder and feedback control algorithm. Because the flexible polymer device has a low Young's modulus, the microactuator need not generate a large force, and it could provide accurate positioning by following the encoder feedback signal.

To evaluate the tunable laser as a WDM light source, the bit error rate (BER) measurement was performed in an optical link as depicted in Fig. 8. A $LiNbO_3$ external modulator was used for high-speed modulation because the current ECL device does not provide sufficient bandwidth because of the long cavity length. The SLD must be connected directly to the flexible grating without the PM fiber if high-speed direct modulation is required. A polarization controller was used to excite TE

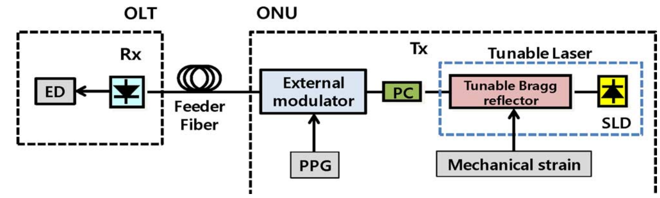

Fig. 8. Configuration of optical transmission experiment; setup consists of the tunable laser operated by an imposed mechanical strain, and an external modulator used to produce a 2.5 Gb/s modulated optical signal.

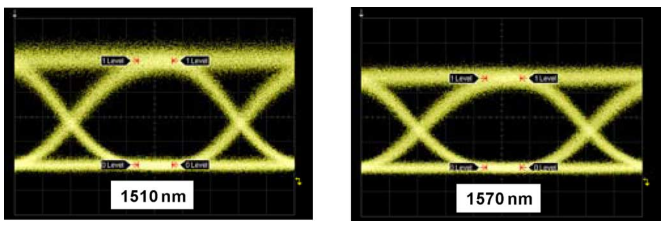

Fig. 9. Eye diagrams of 2.5 Gb/s signal after transmission over a distance of 50 km obtained at 1510 nm and 1570 nm.

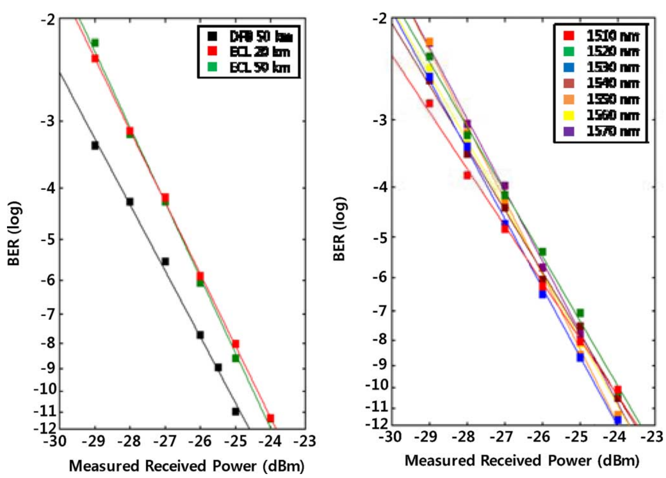

Fig. 10. Measured BER curves of the 2.5 Gb/s signal: (a) ECL compared with a fixed-wavelength DFB laser, and (b) curves obtained for various optical wavelengths from 1510 nm to 1570 nm after transmission over a distance of 50 km.

polarization in the external modulator, which was modulated at 2.5 Gb/s by a pseudo-random binary sequence with a pattern length of $2^{31}-1$. The modulated 2.5 Gb/s signal was transmitted through fiber links with lengths of 20 and 50 km. The wavelength of the ECL was adjusted from 1510 nm to 1570 nm in 10 nm steps. The wavelength range was limited by the spectral bandwidth of the measurement system.

Eye diagrams of the modulated signal at 1510 nm and 1570 nm were obtained after the signal was transmitted 50 km, as shown in Fig. 9. Regardless of the wavelength, the extinction ratio was not degraded from the initial eye pattern, and no additional jitter was observed, indicating that the polymer waveguide ECL had good spectral purity. The measured BER is summarized in Fig. 10. As a reference, the BER measured with a DFB laser is also shown. The polymer ECL has a power penalty of 1 dB compared to the DFB laser. However, the BER has no dependence on the length of the optical link, which means there is no power penalty for transmission distances until 50 km. For all the wavelengths, the BER measurements did not exhibit much difference, and a received power of -24 dBm was achieved for a BER of 10^{-10}.

V. Conclusion

In this work, a tunable laser based on a flexible polymer waveguide Bragg reflector was demonstrated and incorporated into a WDM optical communication experiment. The wide tuning capability of the strain-induced tunable laser made it appropriate for use as a WDM light source covering a wide wavelength range of more than 80 nm. To provide a compact tunable light source, the flexible Bragg reflector was installed on a small moving stage driven by a piezoelectric actuator. The strain-tuned ECL exhibited wavelength stability with a fluctuation of less than 0.1 nm. In the optical transmission experiment, various wavelengths were produced by the tunable laser, and after the 2.5 Gb/s signal was transmitted 50 km, the tunable laser exhibited negligible penalty compared to a fixed-wavelength DFB laser.

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