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# Wideband tunable REC-DFB laser array using thin-film heaters on the submount

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**A wideband wavelength-tunable 4 × 5 distributed feedback (DFB) semiconductor laser array based on the reconstruction-equivalent-chirp (REC) technique using a simple tuning scheme is demonstrated. It consists of 20 DFB lasers with 4 × 5 matrix interleaving distributions, two-level cascaded Y-branch optical combiners, and one active semiconductor optical amplifier (SOA), all in-series integrated on one chip. Unlike the traditional thermal-electric cooler (TEC)-based wavelength-tuning scheme, the tunable 4 × 5 REC-DFB laser array achieves a faster and broader continuous wavelength-tuning range using TaN thin-film heaters integrated on the AlN submount. By changing the injection current of the TaN resistor from 0 to 190 mA, the proposed tunable laser achieves a wavelength-tuning range of ∼2.5 nm per channel and a total tuning of over 50 nm. This study opens up new avenues for realizing cost-effective and wide-tuning-range semiconductor lasers.**

**Keywords:** distributed feedback laser array; reconstruction-equivalent-chirp technique; tunable laser; thin-film heater integrated on the submount; wide tuning range.

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## 1. Introduction

Wideband tunable semiconductor lasers (TSLs) have played significant roles in many optical measurement and communication applications, including fiber sensing interrogators[1], gas-leaking detection systems[2,3], biomedical imaging systems[4], light detection and ranging (LiDAR) measurements[5,6], and wavelength division multiplexing (WDM) transmission systems[7]. Up to now, several TSLs with different structures have been developed, including the external cavity wavelength-tunable laser (ECTL), the wavelength-tunable vertical cavity surface emitting laser (VCSEL), the tunable laser based on distributed Bragg reflector (DBR) structure, and the tunable multi-wavelength laser array (MLA) based on multiple distributed feedback (DFB) lasers. The mechanical scheme of ECTL leads to relatively large footprint and slow tuning speed[8]. The tunable VCSEL has relatively wide spectral linewidth and low output power because of the mechanical microelectromechanical system (MEMS)[9]. The tunable DBR laser is mainly based on the Vernier effect, which has poor mode stabilization and mode hopping during the tuning process[10]. Among them, the tunable DFB-MLA has the advantages of good single-longitudinal-mode operations, narrow spectral linewidth, feasible monolithic integration, and simple wavelength-tuning scheme. The conventional tunable DFB-MLA is tuned by switching different lasers for coarse wavelength selection and then finely tuned by thermal-electric cooler (TEC) to realize continuous wavelength tuning. However, the TEC-based wavelength-tuning scheme is power-consuming, and its tuning speed is severely restricted[11]. Both the wavelength-tuning range and the tuning speed are critical features for TSLs in reducing complexity and cost and improving the performance of optical systems.

In this work, a novel DFB-MLA scheme with wide and fast wavelength-tuning capability is proposed and experimentally demonstrated. We present a 4 × 5 interleaving matrix-grating DFB-MLA fabricated with the reconstruction-equivalent-chirp (REC) technique and design a simple wavelength-tuning scheme by integrating thin-film heaters on the submount. Continuous wavelength tuning of over 50 nm is realized at a tuning speed of 10 nm/s.

## 2. Principle and Design

The conventional tunable DFB-MLA consists of multiple DFB lasers, placed in parallel and monolithically integrated with an optical combiner[12]. However, the optical combiner introduces extra optical power loss and increases the chip size. Furthermore, it needs a heterogeneous integration technique and causes great complexity for the fabrication process. The in-series structure of the DFB-MLA can omit the combiner. However, the single-mode properties of the in-series MLA are vulnerable and easily deteriorated by the grating crosstalk and the reflections of other lasers[13]. Therefore, the designed wavelength spacing of the neighboring lasers needs to be larger than the stopband of the grating, which is typically 3.2 nm, to avoid grating interference[14].

In this Letter, we propose a 20-channel tunable laser array. The gratings of the 20 lasers are monolithically integrated into one chip using $4\times5$ matrix interleaving distribution, which avoids the adjacent grating crosstalk and the extra combination power loss, as shown in Fig. 1. We denote the 20 DFB lasers as LD1 to LD20, whose wavelengths vary linearly from 1530 to 1580 nm with 2.5 nm steps. The adjacent in-parallel lasers have a wavelength spacing of 2.5 nm, and the two adjacent in-series lasers share the same waveguide and have a wavelength spacing of 10 nm. This arrangement avoids the grating interference in the same waveguide to guarantee good single-mode properties[14]. The four in-parallel active waveguides are combined into one output waveguide via two-level Y-branch active combiners. To further amplify and equalize the output power of the DFB-MLA, a semiconductor optical amplifier (SOA) is integrated in front of the optical combiner. The active layer of the DFB laser is an InAlGaAs multiple quantum well (MQW) with five layers, and the p-InGaAsP is used as the grating layer. The proposed tunable laser is manufactured with a ridged-waveguide structure with 2 μm width. The equivalent grating coupling coefficient and the seed grating coupling coefficient of the proposed DFB lasers are approximately $3000\ \mathrm{m}^{-1}$ and $9300\ \mathrm{m}^{-1}$, respectively.

We use the REC technique to fabricate the DFB laser, which can precisely control the designed lasing wavelength and simplify the grating fabrications[13]. With this method, only one step of traditional micrometer (μm)-level photolithography and holographic exposure are needed to fabricate the laser gratings. High-order subgratings can be used to obtain equivalent phase shifts, and we choose the +1st-order subgrating as the laser cavity. When given the grating period of the 0th-order subgrating ($\Lambda_0$) and the variations of the sampling period ($\Delta P$), the variations of the +1st-order subgrating's grating period can be expressed as[15]

$$\Delta\Lambda_{+1}=\frac{1}{\left(\frac{P}{\Lambda_0}+1\right)^2}\Delta P. \quad (1)$$

We can use different sampling periods with the uniform seed grating to achieve different target lasing wavelengths. Then, $\Delta\Lambda_{+1}$ is determined by the $\Delta P$. As a result, the error tolerance of the grating phase can be relaxed by two orders of magnitude[15,16].

Transmission spectra of the five in-series element lasers (LD1, LD5, LD9, LD13, and LD17) on the same waveguide of the proposed $4\times5$ interleaving matrix-grating REC-DFB laser array are depicted in Fig. 2. The Bragg wavelength of the uniform grating ($\lambda_0$) is set at 1620 nm, which is far away from the gain region to avoid lasing. Furthermore, this set makes the sampling period as large as near 5 μm, satisfying the precision of the μm-level lithography fabrication technique. For the proposed REC-DFB MLA, the five marked peaks corresponding to the lasing modes of the five in-series element lasers are induced by the equivalent $\pi$ phase shifts. Wavelength tuning of the DFB laser occurs when the waveguide's effective refractive index varies via either changing the temperature or changing the carrier density. Tuning the laser currents will lead to rapid temperature variations of the DFB laser and can finely tune the lasing wavelength. This tuning scheme is simple and achieves a faster tuning speed compared with the traditional TEC-based temperature tuning scheme[17]. For the DFB laser, it is known that the wavelength temperature coefficient is on the order of 0.1 nm/K[18], and the wavelength injection current coefficient is on the order of 0.01 nm/mA[19]. Thus, the indirect thermal tuning of 2.5 nm needs an injection current variation of ~250 mA, which is too

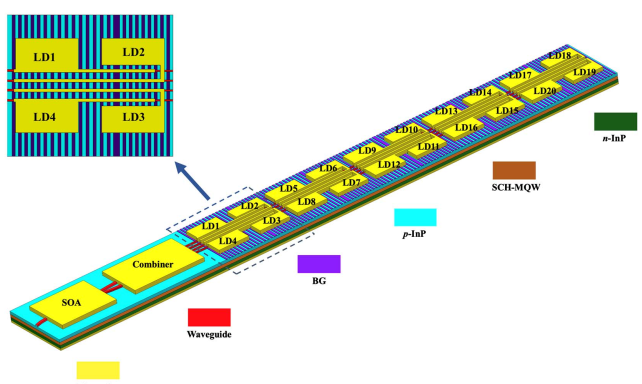


**Fig. 1.** Schematic of the $4\times5$ interleaving matrix-grating REC-DFB MLA (SCH-MQW, separate confinement hetero-structure multiple quantum well; BG, Bragg grating).

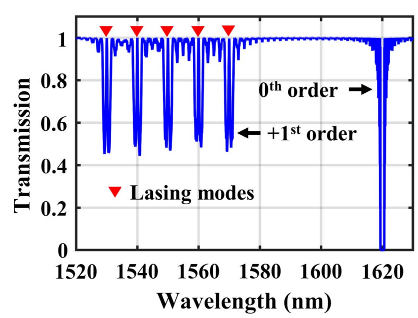


**Fig. 2.** Transmission spectra of the designed five in-series gratings (LD1, LD5, LD9, LD13, and LD17) and the five transmission peaks marked with red triangles corresponding to the lasing modes of the five in-series element lasers.

large to protect the laser. To safely enlarge the tuning range and improve the tuning speed, we propose a scheme by integrating thin-film heaters on the submount of the REC-DFB MLA chip, as depicted in Fig. 3. Specifically, the top-down configuration of the packaged DFB laser contains a laser chip, submount, heatsink block, and TEC. A 10 kΩ negative temperature coefficient (NTC) thermistor is surface-soldered on the TEC to monitor the environmental temperature. Ten 50 Ω thin-film heaters are arranged near the laser chip to improve the heating efficiency.

The thermal conductivity of submount and the thermal contact between the submount and the heatsink can both significantly influence the temperature of the laser chip via thermal simulations and heat conduction analysis[20]. To cover the 2.5 nm wavelength spacing of the proposed REC-DFB MLA, the lasing element laser's temperature needs to increase by at least 25 K. We then adjust the currents of the integrated thin-film heaters on the AlN submount to study the wavelength-tuning effect through thermal simulations. The thin-film heaters on the submount are fabricated by sputtering a high-resistance film of tantalum nitride (TaN) under the conductor layer and selectively etching the resistor elements. The sizes of the standard AlN submount without heaters and the AlN submount integrated with 10 TaN thin-film heaters are both set as $6\,\mathrm{mm} \times 5\,\mathrm{mm} \times 0.254\,\mathrm{mm}$, which is compatible with our existing laser packaging design, as shown in Figs. 3 and 4. Each heater of the proposed submount is in charge of tuning two neighboring lasers. COMSOL is utilized to thermally simulate and compare the REC-DFB MLA chip's temperatures. The laser

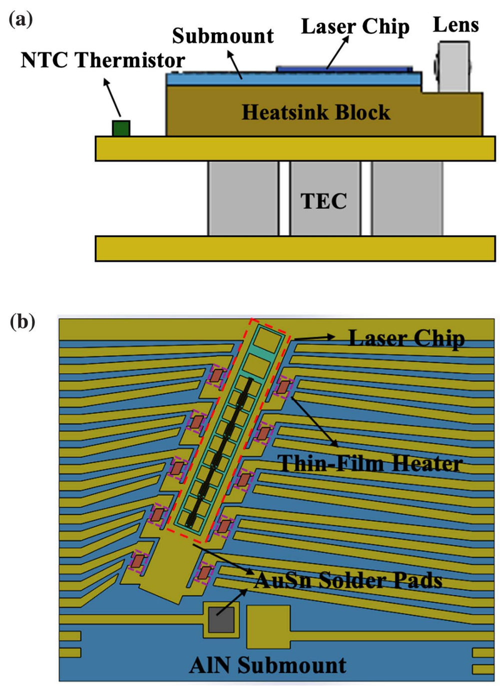


**Fig. 3.** Schematic of the (a) DFB laser packaging configuration and the (b) top view of the $4 \times 5$ interleaving matrix-grating REC-DFB laser array mounted on the submount integrated with heaters (NTC thermistor, negative temperature coefficient thermistor).

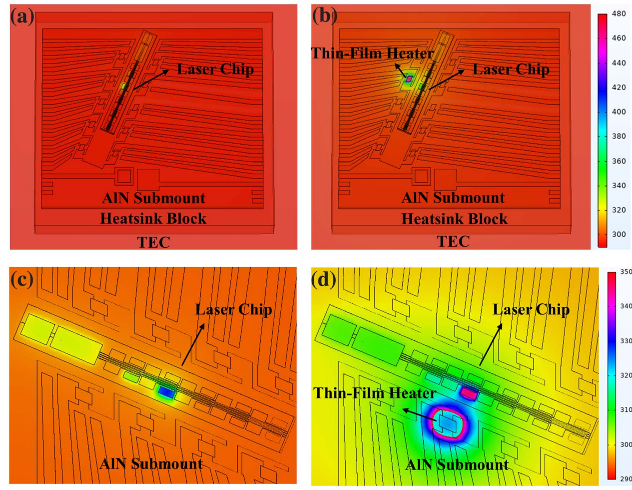


**Fig. 4.** Thermal simulations of the REC-DFB MLA chip's steady-state temperature on the (a) standard AlN submount and the (b) optimized submount integrated with thin-film heaters, with laser injected current of 80 mA and heater injected current of 190 mA. Enlarged view of the temperature distributions for the REC-DFB MLA chip on the (c) standard AlN submount and the (d) submount integrated with thin-film heaters.

thermal power is 240 mW, and the laser injection currents are 80 mA on different submounts. The injection current of the heater on the submount is 190 mA. The steady temperature distributions of the laser chips are shown in Fig. 4, where the active region temperatures of the laser chips on the standard submount and the submount with thermal resistors are 325 K and 352 K, respectively. Thermal simulation results indicate that the optimized submount layout can induce enough temperature variations for the 2.5 nm wavelength-tuning range compared with the standard AlN submount when injected with the same laser current.

## 3. Experiment and Discussion

Figure 5 shows the microscopic photos of the fabricated $4 \times 5$ matrix-grating REC-DFB laser array chip, which has the length of 3050 μm and the width of 400 μm. The lengths of the SOA, optical combiner, and each element laser are 330, 420, and 450 μm, respectively. Both the front and rear facets of the chip are anti-reflection (AR) coated. A 50-μm-long tail absorption region (TAR) is to absorb the light output from the rear facet. The Yokogawa AQ6370 optical spectrum analyzer (OSA) was used to record optical spectra of the proposed tunable laser in the spectral measurement.

Figure 6(a) depicts the superimposed spectra of the 20 lasing element lasers when the SOA current, Y-branch optical combiner current, and laser current are 40, 50, and 80 mA, respectively. For the in-series element lasers, the 30 mA transparency currents were applied to all the lasers in front of the lasing element laser to suppress the material absorption. With the linear fitting results of the lasing wavelengths shown in Fig. 6(b), the proposed REC-DFB MLA chip has a nearly uniform

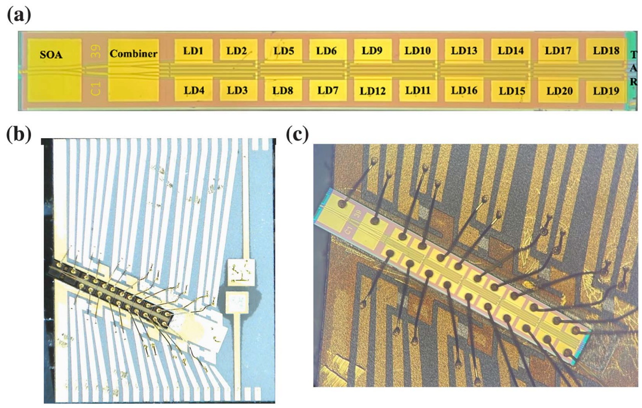


**Fig. 5.** (a) Microscopic view of the 4 × 5 interleaving matrix-grating REC-DFB laser array chip; (b) top view and (c) magnified view of the fabricated 4 × 5 matrix-grating REC-DFB laser array chip on AlN submount integrated with TaN film heaters.

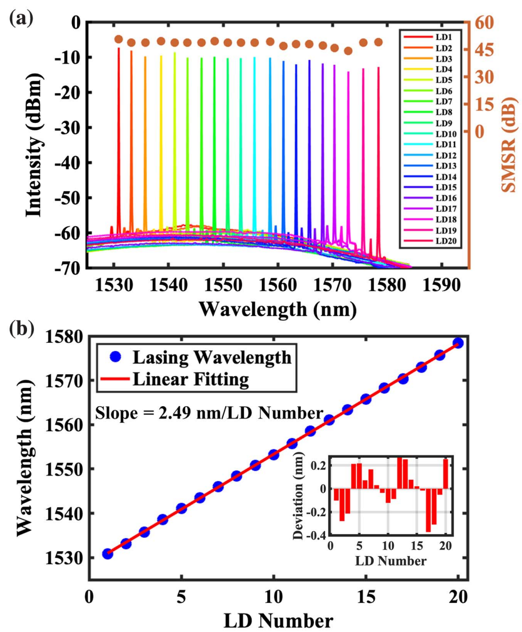


**Fig. 6.** (a) Superimposed lasing spectra of all 20 lasers when the laser current is 80 mA and (b) the lasing wavelength fitting for the 20 element lasers of the REC-DFB MLA, with the wavelength-fitting deviations of the 20 lasers depicted in the inset of (b).

wavelength spacing of 2.49 nm, and the maximum wavelength deviation is less than 0.37 nm.

Figure 7(a) shows the typical *PI* and *IV* diagram of the first four in-parallel lasers when the laser current ($I_{LD}$) changes from 0 to 200 mA, and the SOA current ($I_{SOA}$) and optical combiner current are set as 20 mA and 50 mA, respectively. The measured threshold currents of LD1, LD2, LD3, and LD4 are 30, 32, 32, and 28 mA, respectively. The differential resistances of the LDs are approximately 7.8 Ω. As shown in Fig. 7(b), we studied the integrated SOA amplifying capability via changing the $I_{SOA}$

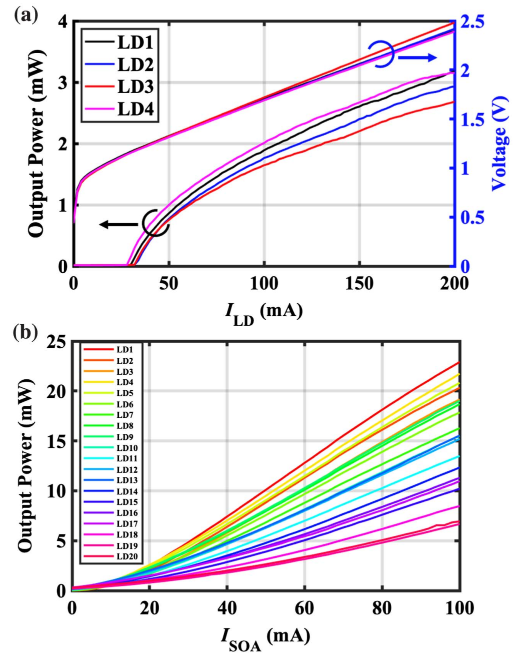


**Fig. 7.** (a) Typical *PI* and *IV* diagram of the four in-parallel lasers with SOA and optical combiner injection current of 20 mA and 50 mA. (b) Output powers of all 20 lasers with the SOA current varied from 0 to 100 mA as well as the optical combiner injection current of 50 mA and laser current of 80 mA ($I_{LD}$, the injection current of laser; $I_{SOA}$, the injection current of the semiconductor optical amplifier).

from 0 to 100 mA. When the currents of SOA, optical combiner, and laser are 100, 50, and 80 mA, the output power of all 20 lasers can be amplified to above 6.5 mW.

The tuning ranges of all 20 lasers of the REC-DFB MLA mounted on the standard AlN submount were subsequently measured. We recorded the corresponding wavelengths when the injection currents of each lasing element laser varied from 40 to 120 mA. The superimposed tuning spectra for the 20 lasers are shown in Figs. 8(a) and 8(b), with an average wavelength tuning of approximately 1.2 nm per laser.

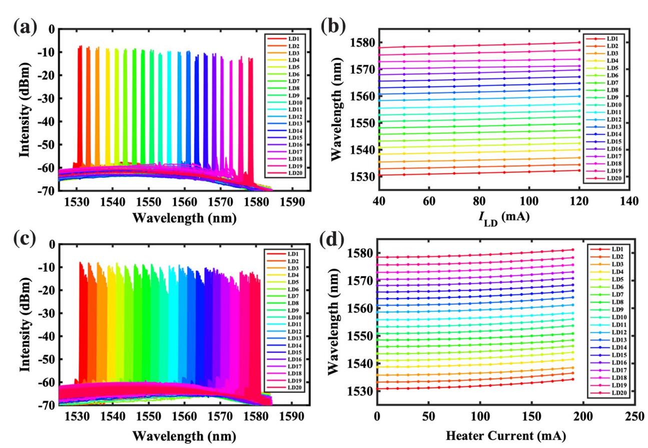


**Fig. 8.** Measured tuning spectra and current-wavelength relationships for the 20 lasers of the REC-DFB MLA mounted on the standard submount and the optimized submount with thin-film heaters, respectively.

As a comparison, we also measured the tuning ranges of the 20 lasers of the $4 \times 5$ REC-DFB MLA mounted on the optimized submount with heaters. The tuning ranges of the 20 integrated lasers are all over 2.5 nm when the thin-film heater's current varies from 0 to 190 mA, as shown in Figs. 8(c) and 8(d). This tuning result meets the expectation of the simulation, which can cover the spacing gap of the DFB-MLA. If necessary, the power fluctuations of each laser during wavelength tuning can be further reduced and equalized by adjusting the SOA current accordingly. By using the integrated TaN thin-film heater on the submount, the tuning range of the $4 \times 5$ REC-DFB laser array is effectively widened from 1.2 nm to 2.5 nm for each element laser to cover the wavelength spacing, achieving a total wavelength tuning of 50.28 nm. Compared with the standard submount, the heater-current-wavelength curves for the thin-film heater on the submount show nonlinear tendency. This is because the variations of the lasing wavelength are mainly induced by heat, whereas the heat and the heater-current have a nonlinear relationship ($Q_{\text{heat}} \propto I^2 R_{\text{heater}}$).

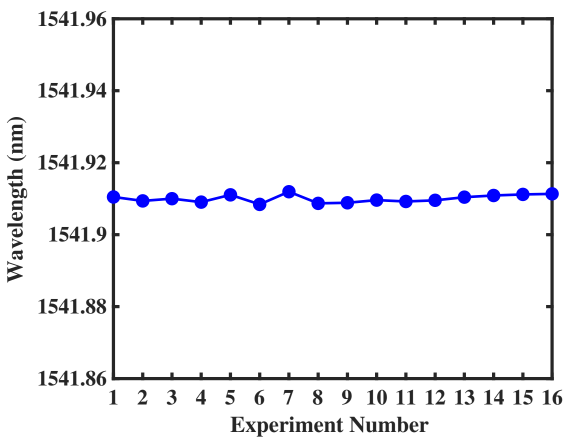


**Fig. 9.** Experimentally measured central reflection wavelength of the same FBG for repeating wavelength-tuning experiments by 16 times.

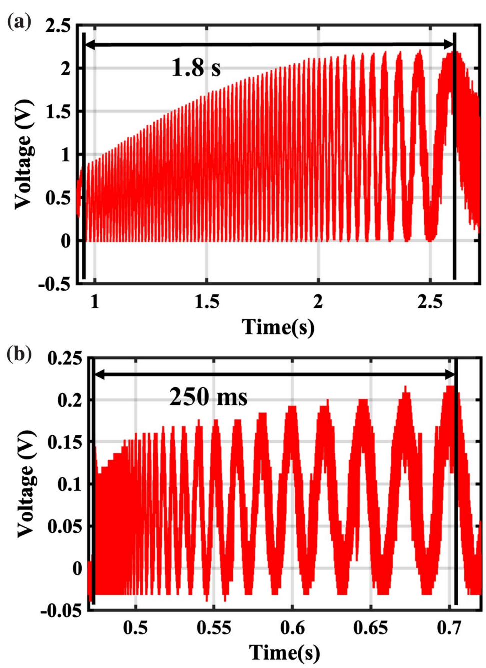


**Fig. 10.** Experimentally measured tuning speed of the (a) TEC tuning scheme and (b) submount heater tuning scheme for 2.5 nm wavelength variations of one element laser using the MZI-based system.

Besides, we examined the repeatability of the proposed wavelength-tuning method using a narrowband fiber Bragg grating (FBG) by monitoring the reflection peak while sweeping the laser's wavelength repeatedly. As shown in Fig. 9, the repeatability is measured to be approximately 0.003 nm after 16 measurements.

Furthermore, we compared the tuning speeds based on TEC and based on the film heater on the submount for one element laser. The wavelength tuning was measured with a Mach–Zehnder interferometer (MZI)-based system[17]. The measured optical intensity fluctuations can indicate the real-time wavelength changes of the laser. As shown in Fig. 10, compared with the traditional wavelength-tuning scheme based on TEC, whose tuning speed is 1.8 s, the proposed scheme needs only 250 ms.

## 4. Conclusion

In this work, we propose and experimentally demonstrate a wideband and fast tunable DFB laser array. The proposed DFB-MLA achieves good single-mode operation and uniform wavelength spacing via the REC technique, which can precisely control the grating phase. With the film heater on the submount, the wavelength-tuning range is widened to 2.5 nm for each element laser and realizes a whole 50 nm continuous wavelength-tuning range. The tuning speed is 7.2 times faster than that of TEC. The proposed wavelength-tuning mechanism is simple and compatible with existing DFB lasers. Furthermore, the wide wavelength tuning of the interleaving matrix DFB-MLA maintains good single-mode properties, which is promising for future distributed multi-sensor measuring applications.

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