PHOTONICS Research

Optical beam steering by using tunable, narrow-linewidth butt-coupled hybrid lasers in a silicon nitride photonics platform

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Chip-scale, tunable narrow-linewidth hybrid integrated diode lasers based on quantum-dot RSOAs at 1.3 μm are demonstrated through butt-coupling to a silicon nitride photonic integrated circuit. The hybrid laser linewidth is around 85 kHz, and the tuning range is around 47 nm. Then, a fully integrated beam steerer is demonstrated by combining the tunable diode laser with a waveguide surface grating. Our system can provide beam steering of 4.1° in one direction by tuning the wavelength of the hybrid laser. Besides, a wavelength-tunable triple-band hybrid laser system working at ∼1, ∼1.3, and ∼1.55 μm bands is demonstrated for wide-angle beam steering in a single chip.

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1. INTRODUCTION

Light detection and ranging (LiDAR) systems are desired for autonomous driving. Beam steerers are the most important components for the implementation of LiDAR in commercial vehicles [1]. Chip-scale optical phased arrays (OPAs) obtained by photonic integration provide cost-effective and high-performance solutions for the beam steering, compared with traditional beam steerers using complex mechanical components, which are bulky and expensive [2]. OPAs can steer optical beams in two different directions to realize the full-range scanning. The simple solution based on a 2D optical antenna array leads to high device complexity with a large array size, high power consumption, and challenging phase control of each antenna [3]. In recent years, a hybrid approach has become popular for addressing these challenges [4,5]. The beam steering in one direction is provided by a 1D waveguide phased array, and beam steering in the other direction is provided by waveguide surface gratings if the wavelength of the input light signals is tuned [6,7]. Therefore, it is important to integrate chip-scale, narrow-linewidth, wavelength-tunable diode lasers with waveguide phased arrays and surface gratings for obtaining fully integrated OPAs [8,9].

Recently, hybrid integrated diode lasers with a greatly reduced Schawlow–Townes linewidth have attracted considerable research interest [10,11]. Hybrid integration can be obtained through different approaches. Monolithic approaches through the direct epitaxial growth of quantum-dot gain media on silicon are still challenging, especially for the efficient coupling of light from the quantum-dot layer into the silicon waveguide layer. The edge coupling and wafer/die bonding are two main methods used for obtaining the hybrid integration. For the wafer bonding method, active chips/wafers are directly bonded on a pre-processed silicon wafer. Then, all the active components are processed. The alignment between the active and passive components is controlled by the lithography accuracy, which is suitable for large-scale integration and manufacturing [1,8]. There are two main concerns with this heterogeneous integration approach. First, for practical manufacturing, the active devices should be pre-tested before the integration process. But, for the heterogeneous integration process, the testing must be done after the whole integrated chip is fabricated. Second, an oxide layer preventing efficient heat dissipation must be used between the active chip and passive waveguide. Instead, hybrid integration via edge coupling is a promising candidate to solve the problems, since the active chips and passive chips can be fabricated and optimized independently [12,13]. Thermal management is also relatively easier in this case. The main drawback of this method is that it does provide good large-scale manufacturing scalability and is only suitable for small-/medium-scale production. In addition to the silicon-on-insulator (SOI) platform [14], high-performance passive optical components have been demonstrated in the integrated silicon nitride (Si_3N_4) platform [15]. Due to the large transparency window of Si_3N_4, multi-band quantum-well gain chips at different wavelength bands can be integrated into the same passive platform [16]. Besides

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quantum-well optical gain chips, quantum-dot gain chips can also be integrated into the same platform through hybrid integration. Quantum-dot gain media provide various attractive advantages, such as a small linewidth enhancement factor, ultrabroad optical gain bandwidth, wide wavelength tunability capability, and low temperature dependence [17–19]. In addition, quantum-dot gain media are good candidates for obtaining uncooled diode lasers, due to strong quantization effects with quasi-zero dimension, which can greatly reduce the total cost and power consumption. Therefore, it is promising to realize the widely tunable narrow-linewidth diode lasers in the quantum-dot reflective semiconductor optical amplifier (RSOA)/Si_3N_4 platform for beam steering.

In this work, we first demonstrate a chip-scale, wavelength-tunable, narrow-linewidth (~85 kHz), hybrid integrated diode laser around 1.3 μm based on a quantum-dot RSOA gain chip and Si_3N_4 external cavity. Then, fully integrated beam steerers in one direction are demonstrated through combining hybrid integrated diode lasers and waveguide surface gratings in a single chip. In addition, we demonstrate a wavelength-tunable triple-band hybrid laser system working at ~1, ~1.3, and ~1.55 μm bands for wide-angle beam steering in chip-scale platforms. Our results are important for providing on-chip narrow-linewidth laser sources with wide wavelength tunability for light detection and ranging applications. In a LiDAR system, the triple-band diode lasers can operate sequentially and use surface gratings with different periods to obtain the continuous steering.

2. LASER DESIGN AND FABRICATION

Figure 1 shows the schematic plot of the hybrid integrated diode laser. It is composed of a quantum-dot RSOA gain chip and $Si_3N_4/SiO_2/Si$ chip. The buried oxide (BOX) layer is 4 μm thick. The RSOA has a high-reflection (HR) coated back-facet with 90% reflectivity and an antireflection (AR) coated front facet. In order to efficiently couple the light between the active and passive chip, a well-designed spot size converter is used to reduce the large mode mismatch between the waveguides in the quantum-dot RSOA and Si_3N_4 chips. The waveguide width of the spot size converter at the input end is 5.9 μm, which is then narrowed down to the single-mode waveguide width. The total length of the converter is 50 μm. The detailed design and simulation results of the spot size converter are described in Refs. [20,21]. The experimentally measured coupling loss of less than 2 dB is obtained. Besides, the RSOA and Si_3N_4 waveguide are both angle-cleaved for eliminating the reflection at the interface between the RSOA and passive chip. The Si_3N_4-based external cavity consists of double-ring micro-resonators with slightly different radii acting as a wavelength filter and extended cavity. The radii for the two microrings are 51 and 54 μm, respectively. A Sagnac loop mirror at the Si_3N_4 waveguide output port is used here to reflect the light back into the laser cavity. The reflectivity is around 50%. The width of the single-mode Si_3N_4 waveguide is set to be 800 nm, and the height is 300 nm. The propagation loss of the single-mode Si_3N_4 waveguide is ~0.50 dB/cm for the 1.55 μm wavelength. The hybrid composite laser cavity is composed of the RSOA, two microring resonators, loop mirror, and input/output waveguides. Micro-heaters are used to thermally tune the resonance wavelength of microring resonators for obtaining the wavelength tunability.

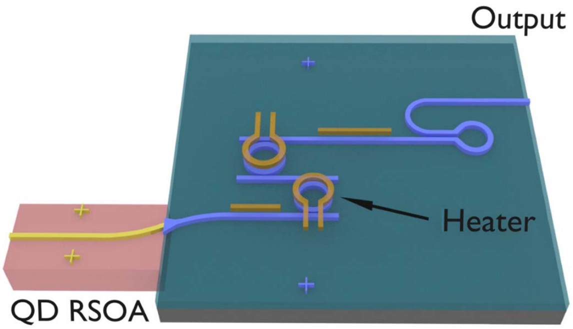

Fig. 1. Schematic plot of the hybrid integrated diode laser.

The passive chip fabrication process is summarized here. A 300 nm thick Si_3N_4 thin film is first deposited on a SiO_2/Si wafer using Tystar nitride low-press chemical vapor deposition tool. We pattern and etch the Si_3N_4 waveguide by using electron beam lithography (EBL) and reactive ion etcher. After the Si_3N_4 waveguide is fabricated, if needed, the surface waveguide grating is patterned and etched using EBL and plasma dry etching on top of the waveguide. Then, a 1 μm thick SiO_2 cladding layer is deposited on top of the device. Chromium/platinum (Cr/Pt) heaters are deposited and patterned over the resonators for thermally tuning the microring resonators.

3. EXPERIMENTAL RESULTS OF THE HYBRID LASER

An active alignment method is used here to demonstrate the hybrid integration of the RSOA and passive chip for simplicity. The laser light output is collected and measured from the passive chip output port. Figure 2 shows the experimental results of the hybrid integrated laser based on the quantum-dot RSOA gain chip. The light intensity-current (*L-I*) curve for the laser with the threshold current of 95 mA is shown in Fig. 2(a). The slope efficiency is 0.05 W/A. Figure 2(b) shows the output optical spectrum (the pump current is set at 180 mA). The single-frequency lasing with ~50 dB side-mode suppression ratio is obtained due to the Vernier effect between the two microrings with different FSRs. A delayed self-heterodyne interferometer with a 10 km delay line is used here to measure the laser spectral linewidth [10]. The red dots in Fig. 2(c) show the measured RF-beat spectrum. The black line corresponds to a Lorentzian fit. The full width at half maximum (FWHM) laser linewidth obtained is 85 kHz. The linewidth of the hybrid laser is reduced mainly due to the increased effective cavity length and small linewidth enhancement factor of the quantum-dot gain material. The superimposed spectra are shown in Fig. 2(d) when one of the two microresonators is thermally tuned. The wavelength tuning range of ~47 nm is obtained.

4. EXPERIMENTAL RESULTS FOR THE BEAM STEERING

In this section, we demonstrate an on-chip, fully integrated, beam steering system through hybrid integration of the quan-

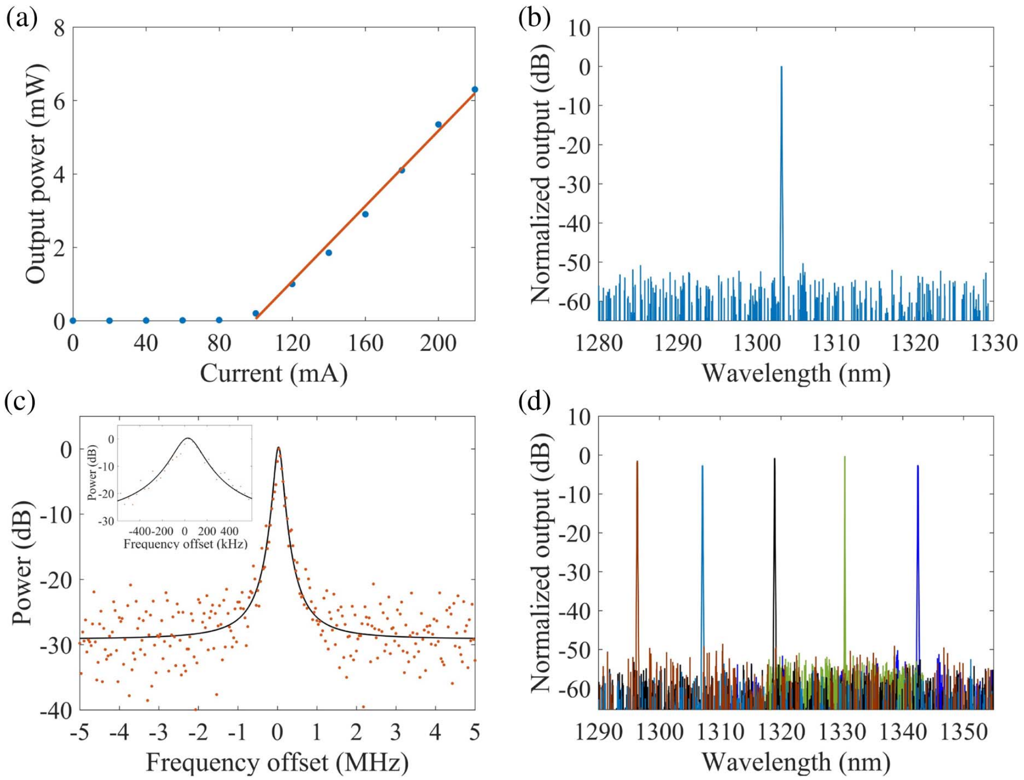

Fig. 2. Experimental results of the hybrid laser. (a) *L-I* curve. (b) Measured optical spectrum with the single frequency operation. (c) Recorded RF beat spectrum (red dots). Black line shows a Lorentzian fit corresponding to a laser linewidth of 85 kHz. Inset shows the detail of the spectrum in a sub-MHz range. (d) Superimposed spectra when thermally tuning one of the two microresonators (the tuning range is ∼47 nm).

tum-dot gain chip, microring-based delay-line filters, loop mirror, phase tuners, and waveguide surface gratings all together. Tunable diode lasers are well suited for a wide range of applications [22]. Here, we show one potential application in beam steering. As shown in Fig. 3, the tunable diode laser combined with a waveguide surface grating can provide beam steering by tuning the wavelength of the light signals. The inset in Fig. 3(a) shows the SEM image of the fabricated waveguide surface grating. The light propagating in the waveguide is scattered and emitted from the surface grating to form a beam in the far field.

The beam propagation direction is tuned if the wavelength of the tunable diode laser is changed. The beam emission angle θ is given by Eq. (1):

$$\sin\theta = \frac{n_{\text{eff}}\Lambda - \lambda_0}{\Lambda}, \tag{1}$$

where n_{eff} is the effective index of the grating, Λ is the grating period, λ_0 is the wavelength, and θ indicates the angle of the output beam with respect to the axis orthogonal to the chip plane.

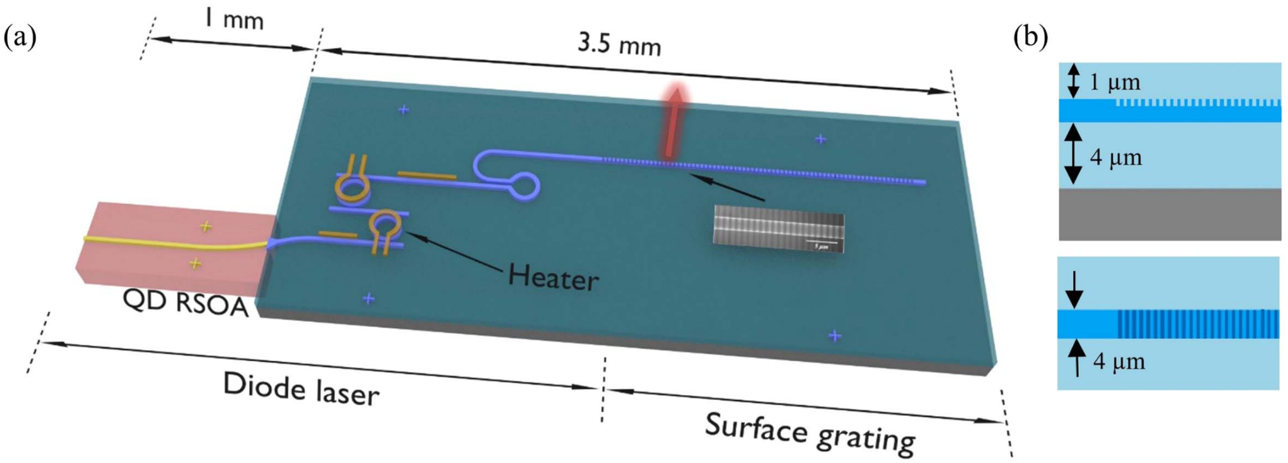

Fig. 3. (a) Schematic plot of the integrated beam steering hybrid system. (b) Side view and top view of the surface waveguide grating.

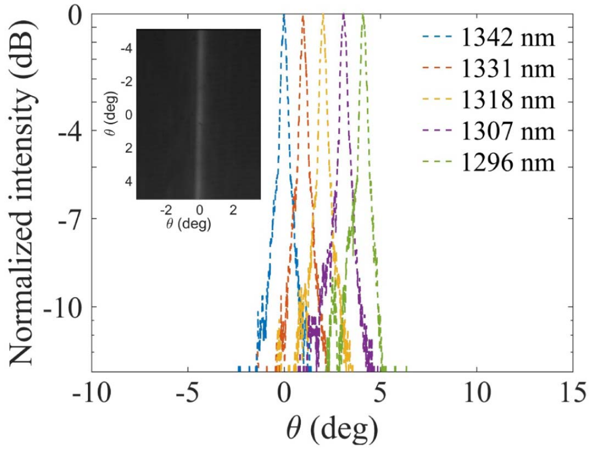

Fig. 4. Experimental results of the beam steering system with the hybrid integrated diode laser based on the quantum-dot RSOA. Inset: far-field IR image of the emission from the surface grating.

The side view and top view of the surface grating are shown in Fig. 3(b). The grating period is 805 nm. The duty cycle is 50%. The 1 μm wide Si_3N_4 waveguide is gradually widened to 4 μm prior to the surface grating. The etching depth of the surface grating is 80 nm, which can distribute the emission over 100 μm length of the grating and thereby maintain a narrow beam in the far field.

Our design allows beam steering by adjusting the wavelength of the hybrid integrated diode laser. In order to measure the far field emission profile of the surface waveguide grating, we use the approach presented in Refs. [23,24]. Figure 4 shows the experimental results of the beam steering by use of the integrated tunable diode laser. The inset shows the far-field IR image. The FWHM beam width is measured to be ~0.4 deg along the grating direction. The beam steering result of the tunable diode laser working at ~1.3 μm is shown. The tuning range is around 4.1°. The steering range is limited by the wavelength tuning range of the hybrid integrated diode laser. The steering range can be improved by increasing the wavelength tuning range of the diode laser or group index of the grating emitter using photonic crystal structure [25].

It should be pointed out that the wavelength tuning range of a single diode laser is usually around several tens of nanometers, which is limited by the emitting wavelength range of the gain material. To increase the beam steering range, multiple laser sources with different gain media working at different wavelength bands can be used [16]. By integrating multiband laser sources on a single photonic chip, an ultra-broadband tunable laser source can be obtained for wide-angle beam steering. In our previous work [10], chip-scale, narrow-linewidth, hybrid integrated, dual-band diode lasers based on the InP/GaAs RSOA and Si_3N_4 external cavity are demonstrated. Single-frequency lasing at 1.55 and 1 μm bands is obtained with the tuning range of 46 and 38 nm, respectively. In this work, the wavelength-tunable, narrow-linewidth diode laser based on quantum-dot RSOAs at 1.3 μm is demonstrated. Thus, it is feasible to create a wavelength-tunable triple-band diode laser system working at 1, 1.3, and 1.55 μm bands on a single chip platform. Figure 5 shows the schematic plot of the triple-band diode laser integrated with surface waveguide gratings. Each RSOA is mounted on an independent stage for accurate control of coupling with the passive Si_3N_4 cavity.

To control the light beam emitted independently, hybrid diode lasers working at 1, 1.3, and 1.55 μm bands are combined with surface gratings A, B, and C, respectively. The grating B has the same parameters as those shown in Fig. 3.

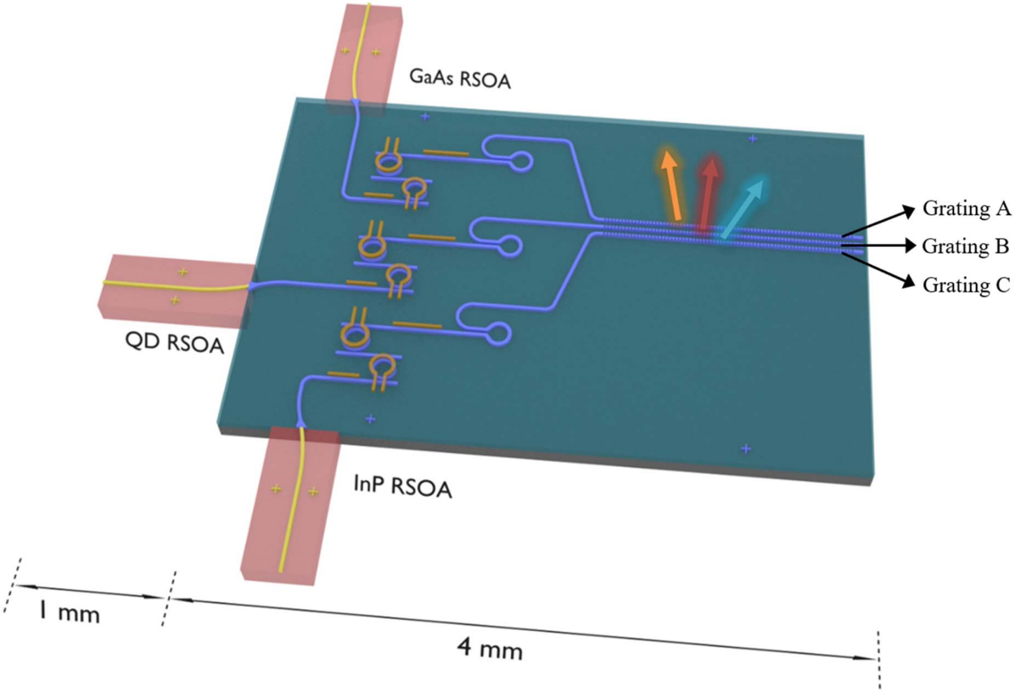

Fig. 5. Schematic plot of the integrated beam steering hybrid system with the triple-band diode laser.

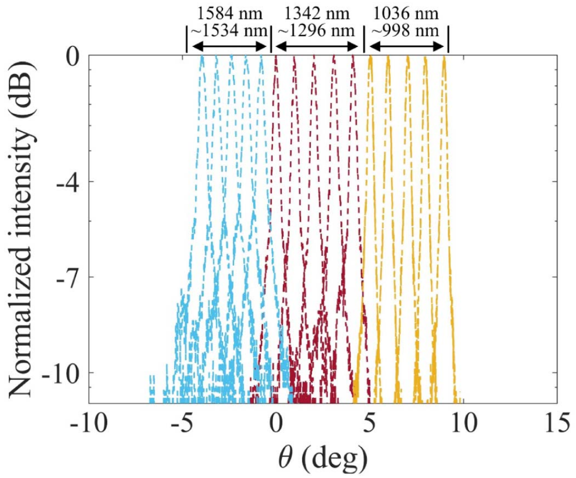

Fig. 6. Experimental results of the beam steering system with the hybrid integrated triple-band diode laser. The periods of gratings A, B, and C are 632, 805, and 931 nm, respectively.

The periods of gratings A, B, and C are 632, 805, and 931 nm, respectively. Other geometric parameters of all the waveguide gratings are the same. Figure 6 shows the experimental results of the beam steering system with the hybrid integrated triple-band diode laser. The beam is tuned from 9° to 5° (from 4° to 0°, from −0.8° to −4°), when the wavelength of the hybrid diode laser is tuned from 998 to 1036 nm (from 1296 to 1342 nm, from 1534 to 1584 nm). The total beam steering range is increased to be around 13°.

Figure 7 shows the experimental results of the beam steering system when the gratings A, B, and C have the same grating period of 805 nm. The beam can be tuned at around 27°, 2°, and −18°. The beam steering range is also greatly increased, compared with that using only one RSOA gain chip. Here, we use three different surface gratings with the same design for beam steering. But the triple-band diode lasers have to use a single waveguide grating for obtaining a compact waveguide phased array, which provides the beam steering in the other direction. The light from different diode lasers can first be coupled into a single waveguide through broadband beam combiners, as proposed in Ref. [26]. Then, the light can be split into a waveguide phased array. For now, we only demonstrated the tunable triple-band diode lasers working at 1, 1.3, and 1.55 μm bands. If we integrate multiple gain chips into the same Si_3N_4 platform, however, the wavelength of the laser source can be continually tuned in a wide range from 1 to 1.6 μm, which leads to a wide steering range of >50°. The beam steering in the other direction can be provided by a waveguide phased array. Thermal tuning is used here for our devices due to its negligible optical loss. But thermal tuning has a few drawbacks in terms of slow tuning speed, crosstalk, and high-power consumption. An ideal thermo-optic phase shifter has a relatively low bandwidth of a few kHz resulting in limited beam scanning speed [8,27]. In order to realize the high-speed tuning, we are planning to create our passive components in a lithium niobite platform with the Pockels effect, although the integration of such a platform within a laser cavity has not been demonstrated. In a phased array system, light of different wavelengths travelling at different speeds in optical waveguides could introduce a beam squint problem. Due to the large wavelength range used here, the steering direction could be off a few degrees for different wavelengths. The problem could be avoided in an optical waveguide phased array system, since the phase section of each optical waveguide can be individually controlled with a true time delay line. In practical applications, the eye damage threshold at the 1 μm wavelength is relatively low. In order to avoid the potential problem, we can use the wavelength range between 1.2 and 1.7 μm or use the coherent detection.

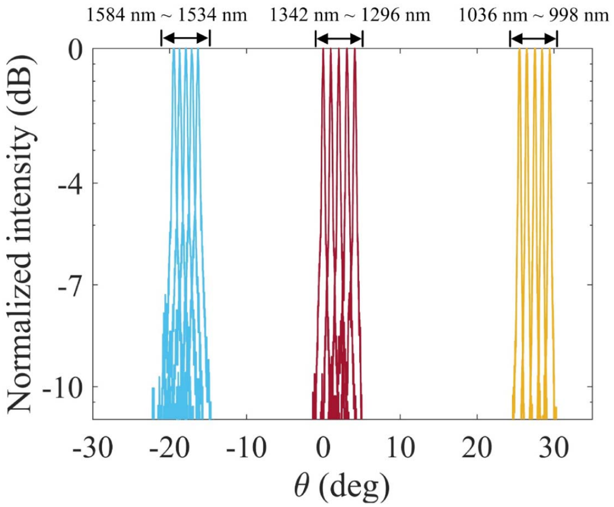

Fig. 7. Experimental results of the beam steering system with the hybrid integrated diode laser. The periods of gratings A, B, and C are the same.

5. CONCLUSION

We have demonstrated the hybrid integration of a low-loss, passive Si_3N_4 external cavity with a quantum-dot RSOA at 1.3 μm in the silicon nitride photonic integration platform. The laser linewidth obtained is around 85 kHz, and the tuning range is around 47 nm. Our system has the potential to provide on-chip narrow-linewidth laser sources with wide wavelength tunability for passive photonic integrated circuits. In addition, we demonstrate a beam steering system through hybrid integration of the tunable diode laser based on the quantum-dot RSOA with a waveguide surface grating. Beam steering is obtained over a range of 4.1° when the wavelength of the hybrid diode laser is tuned. By integrating two additional RSOAs at 1 and 1.55 μm bands into the same silicon nitride platform, the beam steering range is greatly increased to be 13°.

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