Abstract—We propose a tunable dual-wavelength heterogeneous quantum dot laser diode. The tunable dual-wavelength laser consists of a quantum dot semiconductor optical amplifier as the optical gain medium and an external cavity fabricated from silicon photonics technology as the wavelength tunable filter. We successfully demonstrated dual-wavelength lasing oscillation by tuning the difference frequency from approximately 34 to 400 GHz.

Index Terms—Quantum dot laser, semiconductor laser, silicon photonics.

I. INTRODUCTION

IN RECENT years, information and communication traffic have exponentially increased. In particular, the increase in traffic for datacenters and access networks, including wireless links, has been higher than that for other networks [1] because the last connection from the Internet to individual users is mostly based on wireless communications. Moreover, the spread of smart devices such as smartphones and tablet PCs and the enrichment of various service contents are being greatly promoted. Therefore, ultrafast and high-capacity photonic networks are urgently required. More convenient communication and connectivity are expected in the next generations of advanced wireless services, such as beyond 5G mobiles. To satisfy these requirements, advances such as a communication speed of more than 10 Gb/s, high capacity, low latency, and low-cost services need to be achieved. To meet this need, realizing the transparent transfer of signal waveforms between optical and wireless communications is very important. Radio-on-fiber (RoF) is a promising technique [2]. One of the issues with establishing a seamless connection between optical and radio links is the capacity bottleneck from the speed mismatch between 100 Gb/s class optical fibers and conventional 1 Gb/s class wireless communications. Therefore, the carrier frequency of radio communications needs to be changed from the conventional microwave band to the millimeter-wave band. In high-speed communication across RoF links, two important elements are a millimeter-wave generation technique that can operate at a frequency of greater than 100 GHz and an ultrafast photodiode as an optical/radio conversion device [3]. Optical two-tone signals with frequency separation by the millimeter wave can be seamlessly converted into radio signals by envelope detection using an ultrafast photodiode, as shown in Fig. 1. Typical two-tone generating techniques involve using modulation sidebands or two laser diodes (LDs) [4]–[6]. A dual parallel Mach–Zehnder modulator (DP-MZM), which enables high extinction ratio operation and precise frequency control of optical two-tone signals, has been reported as a possible candidate for a clear millimeter wave generator. However, a more compact optical two-tone signal generator is necessary to realize advanced optical and wireless seamless networks; these include communications and sensor networks such as the Internet of Things, in which the RoF technique plays an important role because the relatively large footprint of the DP-MZM limits further applications. Thus, the use of two individual LDs or monolithically integrated two arrayed LDs is characterized by a compact device size and low consumption energy. However, because of the independent behaviors of the two LDs, the difference frequency of the two lasing wavelengths tends to have a relatively large fluctuation.

So far, we have demonstrated compact and high-performance wavelength-tunable LDs composed of III–V gain medium and Si photonics-based external filters utilizing heterogeneous materials, which can be tuned over a wide range of wavelengths [7]–[9]. However, these LDs require external tuning methods, such as heaters or gratings, which are not suitable for on-chip integration. Therefore, it is desirable to have a tunable dual-wavelength LD that can be fabricated on a single chip and can be externally driven without using external components. To achieve this, we propose a tunable dual-wavelength heterogeneous quantum dot laser diode.

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integration technology [7]–[9]. Moreover, we have developed a high-density and high-quality quantum dot (QD) structure [10], which is a promising material because the density of states forms a delta function-like shape [11]. In addition to other groups, we have also demonstrated high-performance optical devices with QD structures such as LDs [12]–[19], semiconductor optical amplifiers (SOAs) [20]–[23], optical frequency comb sources [24], modulators [25], photodiodes, and nonlinear functional devices [26] that exhibit a high modulation bandwidth, high temperature stability, ultrafast response, low threshold current, low chirp, low consumption energy, and so on. We have also presented a wavelength-tunable heterogeneous QD-LD with the two kinds of technologies mentioned above [27], [28]. On the other hand, there is an issue to decrease the device size although we previously proposed and successfully demonstrated the dual-mode laser using only one QD gain chip with the external cavity as reported in the reference [29], which was owing to the properties of QDs such as size fluctuation and spatially isolated structures.

In this paper, we propose a difference frequency tunable dual-wavelength heterogeneous QD-LD with a Si photonics-based photonic integrated circuit (PIC) for realizing high-capacity millimeter-wave RoF communications [30]. We successfully demonstrated dual-wavelength lasing by tuning the difference frequency from approximately 34 GHz to 400 GHz by controlling the refractive index of the filter on a Si external cavity. Additionally, we indicated the potential of the dual-wavelength heterogeneous QD-LD, which had a difference frequency of more than 650 GHz between the two lasing wavelengths in the experimental configuration, where the QD gain chip and Si photonics-based PIC were used individually from each other.

II. DESIGN OF THE SILICON PHOTONIC EXTERNAL CAVITY

The dual-wavelength tunable LD consists of a QD-SOA as the optical gain medium for lasing and an external cavity fabricated from silicon photonics technology for wavelength tuning operation. Although multi-wavelength LDs with a silicon photonic external cavity have previously been reported, their frequency differences were fixed [18], [31]. Our tunable LD allows us to generate an arbitrary frequency difference because each wavelength is independently controlled. Fig. 2 shows the schematic of the external cavity for a dual-wavelength tunable LD. The spot size converter (SSC) uses a tapered silicon waveguide and SiOx cladding structure to provide high coupling efficiency to the QD-SOA or optical fiber [32]. The lightwave emitted from the QD-SOA is filtered by a micro-ring resonator (Ring 1), and resonant wavelengths of Ring 1 are dropped to a distributed Bragg reflector (DBR1). The only resonant wavelength of Ring 1 is reflected by DBR1 because the reflection wavelength range of the latter is designed to be narrower than the free spectral range (FSR) of the former. Thus, one mode with the wavelength controlled by one ring resonator and one DBR is reflected to the QD-SOA, and single-mode laser oscillation occurs. The resonant wavelength of the ring resonator can be controlled by the micro-heater placed on the ring resonator. One unit containing one ring and one DBR acts as a wavelength tunable filter for the lasing wavelength $\lambda_1$. The lightwave through Ring 1 without resonance is filtered by Ring 2, which has a different resonant wavelength from Ring 1. The lightwave with wavelength $\lambda_2$ is reflected to the QD-SOA by the unit of Ring 2 and DBR2. This silicon photonics external cavity acts as a multi-wavelength filter. Each wavelength is independently controlled with high optical reflectance.

Table I presents the design parameters of the tunable filters. The FSR of the ring resonator is inversely proportional to the circumference of the ring; ultra-small ring resonators fabricated from silicon photonic wire waveguides can easily realize an FSR of several hundred gigahertz. Although the large finesse of the ring resonators allows fine control of the wavelength, the insertion loss of the ring resonators also increases. Because the optical gain of QD-SOA is smaller than that of the conventional SOA made of InGaAsP quantum wells, the laser oscillation of our laser is inhibited in an external cavity where the finesse is too large. A relatively small finesse of 13.9 was used for stable laser oscillation. The waveguide width is periodically modulated in the DBR structure [33].

Fig. 3 shows the calculated reflectance values of the Ring 1/DBR1 unit and Ring 2/DBR2 unit. The reflection bandwidths of the DBRs are also shown. The reflectance difference between the selected and nearest-neighbor resonant wavelengths was designed to be more than 4 dB. The modal gain difference between $\lambda_1$ and $\lambda_2$ needs to be as small as possible for stable dual-wavelength laser oscillation. The modal gain differences depend on the frequency difference between the two laser oscillations were calculated, as shown in Fig. 4. The modal gain difference rapidly increased when the frequency difference was less than 100 GHz because the reflectance of $\lambda_2$ decreased.
The input light of Ring 2 through Ring 1 and the power of the propagation light decreased when the resonant frequencies of the two rings were too close. The modal gain difference increased when the frequency difference was more than 600 GHz because the resonant wavelength fell outside the reflection bandwidth of the DBRs. The reflection wavelength of DBRs can be tuned by using heaters placed on the DBRs, and the maximum frequency difference is increased to more than 1 THz by using DFB heaters. However, DFB heaters were not used in this study because the thermal cross-talk between the ring heaters and DFB heaters was a serious problem for stable control of the wavelength tuning operation. This problem can be resolved by using thermal insulation grooves. Assuming that the tolerance of the modal gain difference for dual-wavelength lasing is 3 dB, the wavelength tunable filter can generate a frequency difference from 40 GHz to 650 GHz without DFB heaters.

III. MEASUREMENT

A. Single-Mode Wavelength Tunable Laser Diode

A single-mode wavelength tunable filter with one designed ring resonator and one designed DBR was fabricated by using silicon photonics technology. One waveguide facet of the QD-SOA was given anti-reflection coating, and the other waveguide facet was cleaved with 30% reflection. The waveguide facet with AR coating was connected to the silicon photonic external cavity with a small-diameter optical fiber. The laser output was measured from the cleaved facet. The temperature of the QD-SOA was stabilized at 20 °C by a thermoelectric cooler. Obvious laser oscillation was observed with a QD-SOA injection current of 200 mA. Fig. 5 shows the wavelength spectra with various heater input powers. Multi-mode lasing was observed at heater powers of 12.2 and 88.0 mW. Fig. 6 shows the heater input power dependence of the lasing wavelength. The Nth-order resonant wavelength of the ring resonator was linearly controlled by the heater input power. Other resonant wavelengths with different resonant orders of N - 1 and N + 1 were also observed. The cause of the multi-wavelength lasing was the wideness of the reflection frequency range in the DBR. The measured reflection wavelength range was 3.6 nm, which corresponds to a frequency range of 721 GHz, and the measured FSR of the ring resonator was 625 GHz. Although the FSR was narrower than the reflection frequency range of DBR, a wavelength range of 2.1 nm, which corresponds to a frequency range of 421 GHz, was available for single-mode laser oscillation.
B. Dual-Wavelength Tunable Laser Diode

A dual-wavelength tunable LD with two units of ring resonators and DBRs was measured. Fig. 7 shows the SOA injection current dependence of the optical output power. Fig. 8 shows the wavelength spectra from the measured output power. The threshold current was 220 mA, and a lasing wavelength of 1222.6 nm was selected for Ring 1 with a heater input power of 43.0 mW. When an SOA injection current of more than 300 mA was applied, a second lasing peak of 1221.9 nm that was selected by Ring 2 with a heater input power of 31.5 mW was observed. The laser output power of the two wavelengths was almost equivalent to an injection current of more than 400 mA. The maximum total output power emitted from both lasing modes was 0.45 mW when the SOA injection current was 400 mA. Dual-wavelength laser oscillation was successfully demonstrated.

The wavelength was tuned by using a micro-heater placed on each ring resonator. Fig. 9 shows wavelength spectra with various SOA injection currents. The heater input powers of Rings 1 and 2 are 43.0 and 31.5 mW, respectively.

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To improve the continuous wavelength tuning, the apodization technique can be applied.

Finally, the frequency differences between the two wavelengths were measured. The wavelength spectra of the maximum and minimum frequency differences are shown in Fig. 13.
The maximum frequency difference reached 400 GHz when the heater powers of Rings 1 and 2 were 67.5 and 20.7 mW, respectively. The measured maximum frequency difference was less than the design value of 650 GHz because the available frequency range with one ring resonator and one DBR decreased owing to the wideness of the DBR reflection frequency range. By using a ring resonator with a larger FSR, the maximum frequency difference can be further expanded. The minimum frequency difference was 34 GHz when the heater powers of Rings 1 and 2 were 43.0 and 43.5 mW, respectively. The smallest frequency difference was restricted by the Q-factor of the ring resonator. Using a high Q-factor ring resonator will reduce the minimum frequency difference. The wavelength tunable dual-wavelength laser was successfully demonstrated with a side-mode suppression ratio of more than 35 dB. The two lasing wavelengths were independently controlled by each micro-heater, and the tunable frequency difference range was from 34 GHz to 400 GHz. The previous presented devices with two wavelength laser outputs require two SOAs and two laser cavities [34], [35]. The output wavelengths of these devices have to be precisely controlled for the differential frequency. Our proposed device allows simple control for the frequency of millimeter waves by a micro-heater because the laser modes share the same SOA and same laser cavity. Our device structure with one SOA and one laser cavity also brings a significant benefit with regard to the device footprint and power consumption for the SOA and thermoelectric cooler of the SOA. The actual footprints of the QD-SOA and wavelength filter are 2 mm × 0.3 mm and 1.5 mm × 2 mm, respectively.

IV. CONCLUSION

A dual-wavelength tunable laser was fabricated by using a QD-SOA and silicon photonic external cavity. The two wavelengths were independently controlled, and satisfactory wavelength controllability was demonstrated. A broadband frequency range from 34 GHz to 400 GHz was covered by the frequency difference of the dual-wavelength laser output. The heterogeneous dual-wavelength LD will be an effective light source for a seamless connection between optical and radio links to eliminate the capacity bottleneck from the speed mismatch between high-speed optical fibers and more conventional wireless communications.

REFERENCES


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