Monolithic Dual-wavelength Laser Array Based on Four Phase-Shifted Grating and Equivalent Chirp Technology

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Abstract A monolithic dual-wavelength laser array based on four phase-shifted grating and equivalent chirp technology is proposed and experimentally demonstrated. The experimental results indicate that the array is capable of generating 66.8-73.6 GHz RF signals, with the signal linewidth less than 176 kHz. ©2023 The Author(s)

1. Introduction

Due to the extremely low loss and low cost of optical fibre transmission systems, using photonics technology to generate microwaves has considerable application prospects in fields such as radio-over-fibre, lidar, and wireless communications [1]. Normally, the approach for generating microwaves in the optical domain is to beat two optical signals generated by two separate single longitudinal mode (SLM) lasers and the beating signal has a frequency equal to the frequency difference of the two optical signals. However, as the external temperature can affect the two separate lasers differently, the stability of the microwave signal is susceptible.

Here, we report a monolithic dual-wavelength laser (DWL) array for microwave signal generation. For each DWL, the two optical signals can be generated in one cavity by injecting current through a single electrode on the ridge waveguide. The impact of temperature variations on the frequency difference between the two lasing modes is negligible since the temperature drift affects the two lasing modes identically.

Dual-wavelength lasing is achieved by introducing two π phase shifts at positions 1/3 and 2/3 along the length of the DFB laser cavity [2]. The four phase-shifted (4PS) grating is applied in the DFB cavity, where this structure can demonstrate two advantages. First, the chirp be equivalently realized by linearly can modulating the sampling period at the micron level, which greatly reduces the implementation difficulty compared to modulating the seed grating period at the nanometer level. Consequently, the peaks in the photon distributions of the two lasing modes are separated along the cavity, and mode competition between the two lasing modes can

be largely suppressed [2]. Second, the grating coupling coefficient of the +1st channel can reach 0.9 times that of the uniform Bragg grating, whereas, in the conventional sampled grating, this value is only $1/\pi$ [3]. An electro-absorption modulator (EAM) section is also integrated with the DFB laser to enhance the phase locking between the two lasing modes. By setting a series of chirp rates of 30-90 nm/mm, we obtained the ratio frequency (RF) signals from 66.8 GHz to 73.6 GHz, with a linewidth range from 109 kHz to 176 kHz. Furthermore, the device is based on sidewall grating, which needs only one metalorganic vapor-phase epitaxy (MOVPE) step and one III-V material etching process, simplifying the device fabrication process. The device has the potential to become a compact microwave source.

2. Device Implementation and Experimental Results

The epitaxial structure of the device is based on the AlGaAsIn/InP material system, contains five quantum wells (QWs) and six quantum barriers (QBs), and is described in [4]. The schematic of the fabricated device is shown in Fig. 1(a). The device comprises an EAM section (30 µm), and a DFB section (700 µm), separated by an electrical isolation groove (20 µm). The ridge waveguide is 2.5-µm-wide and 1.92-µm-high, the effective index n_{eff} of the guided mode at 1550 nm is calculated to be 3.19, the sampling gratings are modulated along the DFB laser cavity with a linear chirp rate as shown in the attached figure. The scanning electron microscope image of the etched grating is shown in Fig. 1(b). For 4PS structure, the grating in each sampling period is evenly divided into four sections with each adjacent grating section subjected to a $\pi/2$ phase



Fig. 1: (a) The schematic of the proposed device, the inset figure is the sampling period distribution along the cavity. (b) The scanning electron microscope image of the etched sidewall grating. (c) Microscope image of the DWL array.



Fig. 2: Measured results of the device with 30 nm/mm chirp rate, (a) 2-D optical spectrum map when the EAM reverse voltage V_{EAM} = -1.7 V, (b) optical spectrum with injection current I_{DFB}=75 mA and V_{EAM}= -1.7 V. (c) P-I curve when V_{EAM}= -1.7 V.

shift. Both sidewalls have the same gratings with a period of 257 nm, and the average sampling period is 4.68 μ m to ensure the lasing center at 1555 nm. The grating pattern with 0.6 μ m recess depth is defined by electron-beam lithography (EBL) with a resolution of 0.5 nm using hydrogen silsesquioxane (HSQ) as both a resist and dry etching mask. Fig. 1(c) is the microscope image of the fabricated DWL array.

After fabrication, the devices were mounted epilayer-up on a copper heat sink with a Peltier cooler. The heat sink temperature was set at 20 °C and the devices were tested under CW conditions, with all results measured from the DFB side.

As shown in Fig. 2(a), the device with a 30 nm/mm chirp rate operates in a good dualwavelength lasing condition for DFB currents from 36 mA to 81 mA with -1.7 V applied to the EAM. In Fig. 2(b), two lasing modes λ_1 (1553.69) nm) and λ_2 (1554.25 nm) are clearly observed with an intensity difference of less than 0.02 dB. The smaller the intensity difference between the two modes, the more beneficial it is to improve the quality of the RF signal. Two strong four-wave mixing (FWM) signals (FWM 1 and FWM 2) enhanced by the EAM can also be observed on either side of λ_1 and λ_2 . Fig. 2(c) shows the measured power-IDFB (P-I) characteristics from the DFB side of the device with a scanning step of 2 mA when V_{EAM}=-1.7 V. The threshold current is 24 mA and the slope efficiency is 0.108 W/A.

Tab. 1: Wavelength and operating state of different device.

No.	Chirp rate (nm/mm)	I _{DFB} (mA)	Veam (V)	Δλ (nm)
1	30	75	-1.7	0.555
2	50	98	-1.0	0.564
3	70	126	-0.5	0.575
4	90	158	-0.9	0.589

According to the simulation results, increasing the chirp rate will cause an increase in the wavelength difference $(\Delta\lambda = \lambda_2 - \lambda_1)$ between the two modes. Here, we fabricated four devices with different chirp rates and measured their lasing wavelengths at the optimal state (when the intensity difference between the two lasing modes is minimized), The results and the operating state are shown in Table 1. Obviously, as the chirp rate increases, the $\Delta\lambda$ also increases. It should be noted that the IDFB at which the device reaches the optimal lasing state also become larger with the increase in chirp rate. This is because the increase in chirp rate weakens the grating coupling coefficient, thus the device requires a larger injection to achieve the optimal lasing of the two modes.

The RF signal was measured using a photodetector connected to an electrical spectrum analyzer (ESA) as described in [5]. During the measurement, the operating state of the devices was the same as shown in Table. 1.

As shown in Fig. 3(a), a series of stable RF



Fig. 2: (a) Measured RF spectrum from laser arrays with different chirp rate. (b) Linewidth fit of the device with 30 nm/mm chirp rate when I_{DFB} =75 mA and V_{EAM} = -1.7 V.

 Tab. 2: RF frequency and linewidth under optimal operating state.

	Chirp	RF	RF		
No.	rate	frequency	Linewidth		
	(nm/mm)	(GHz)	(kHz)		
1	30	66.8	176		
2	50	69.5	156		
3	70	71.8	109		
4	90	73.6	160		

signals from different devices were captured by the ESA within a scanning range of 15 GHz. The measured frequency range was from 66.7 to 73.6 GHz, corresponding to the wavelength differences shown in Table. 1. We measured the linewidth of each device at the optimal operating state (shown in Table. 1), with a scanning range of 10 MHz and a resolution bandwidth of 20 kHz of the ESA. As shown in Table. 2, the linewidth range of the array is between 109 kHz and 176 kHz.

3. Conclusions

In this paper, a monolithic DWL array is proposed and experimentally demonstrated. The dualwavelength lasing is achieved by introducing two π phase shifts into the 4PS grating based DFB cavity. The microwave signals, ranging from 66.8 GHz to 73.6 GHz, have been generated by changing the chirp rates from 30 nm/mm to 90 nm/mm. Meanwhile, the typical RF linewidth is in the range of 109 kHz to 176 kHz. The experimental results prove the device has the potential to be a compact microwave source.

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