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Microwave generation with an inner-modulated laser and parallel Mach–Zehnder interferometers

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ABSTRACT

Using an inner-frequency-modulated semiconductor laser, two parallel Mach–Zehnder delay-line interferometers and feedback control loop technique, we generate microwaves. The frequency of the Littrow-structure semiconductor laser is modified by a lead zirconate titanate actuator that covers a wideband modulating range. One long delay-line interferometer generates microwaves; the second short delay-line interferometer controls the linearity of the modulate laser and assures microwave stability by a feedback loop. Thus, this method, in theory, should produce more than one hundred GHz microwave. We experimentally generated 1.743 GHz to 5.134 GHz microwaves. This technology opens a new path for developments in microwave photonics.

1. Introduction

Microwave photonics, since its inception, has contributed to significant advances in a wealth of applications in sensors, communications, and radio detection and ranging (RADAR). In recent years, research investigating new microwave photonics technologies for different applications has surged, leading to numerous reported findings in the last few years.

Research has identified four major ways to generate microwaves using photonic methods. The first is optical injection locking, which uses one master laser, two slave lasers, and a radio frequency (RF) driver modulating the master laser to produce two sideband optical waves: one positive order and one negative order. Then the two sideband optical waves are injected into two slave lasers. The output wavelengths of the two slave lasers are phase-correlated. The beating of two slave lasers generates stable microwaves [1,2]. The second method is optical phase-lock looping, in which the phase of one laser is actively locked to the second laser by an optical phase-lock loop. The light from two lasers beating on the photodetector produces the microwaves. This technology requires that these two lasers have narrow linewidths and phase fluctuations only at low frequencies [3,4]. The third way is microwave generation based on external modulation. In this method, laser light is transmitted into a Mach–Zehnder (MZ) modulator and split into two beams. One beam is modulated by a microwave source. When the two beams meet on the surface of the photodetector, microwaves are generated. Sometimes the MZ modulator can be replaced with a phase modulator. This substitution can eliminate the problem of bias drifting. The external modulation method is the most widely used method to generate microwaves. The cost of this system which includes some external modulation microwave equipments is expensive. The output frequency of the microwave source limits the frequency range of microwaves produced by external modulation [5,6]. The fourth and final method for producing microwaves is the dual-wavelength laser. Systems based on dual-wavelength lasers are simple; they do not require phase-locking between two separated wavelengths because the two laser beams with different wavelengths are generated in the same cavity. Thus, the phase correlation between the two beams is better than what can be achieved using two free-running laser sources [7,8]. The short coming of this method, however, is the difficulty in changing the output wavelength of the dual-wavelength laser. Most dual-wavelength lasers maintain constant output wavelengths. Thus, only one microwave frequency can be generated.

In this paper, we propose and experimentally demonstrate another method for generating microwaves. The similar concept was reported by few papers [9,10], but all of them using the injection current modulation method, in [9] a 2 × 2 four-port evanescent-field fiber coupler and a 1.1 km length single-mode fiber were utilized, this method could not generate single frequency microwave, both of them had no feedback control loop, the frequency of the generated signals were hardly stable. Our method based on the difference in frequencies between two

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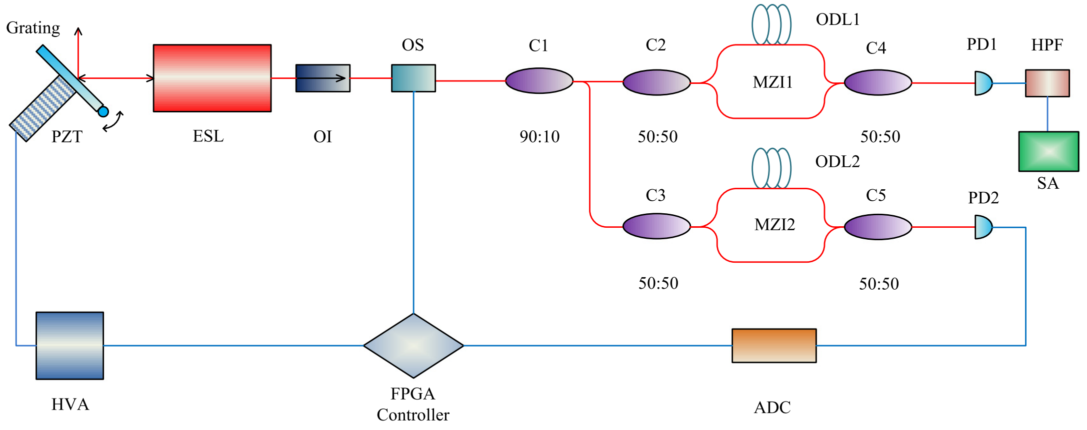

Fig. 1. Microwave generator system scheme. PZT: piezoelectric ceramic actuator; ESL: external semiconductor laser; OI: optical isolator; OS: optical switch; ODL: optical delay line; MZI: Mach–Zehnder interferometer; PD: photodetector; HPF: high-pass filter; SA: spectral analyzer; ADC: analog-to-digital converter; FPGA: field-programmable gate array; HVA: high-voltage amplifier.

wavelengths produced by a Littrow-structured frequency-modulated continuous semiconductor laser, uses two MZ interferometers (MZIs) placed in the system to produce the time delay τ. Then, the output of the photodetector linked with the MZI which has a long fiber delayed line generates the microwave, another MZI with short delayed line is utilized in a feedback control loop to stabilize the microwave. In this experiment, we obtained a pure radio-frequency output from 1.743 GHz to 5.134 GHz. The theoretical model predicts that the frequency range of microwaves generated by this approach can be extended to more than 100 GHz.

2. Experiment system principles

Fig. 1 illustrates the experimental system for generating microwaves. A Littrow-structure external semiconductor laser (ESL) serves as the optical source. Its cavity contains an optical grating. The grating is affixed to a lead zirconate titanate (PZT) piezoelectric ceramic actuator. When the ramp waveform, amplified by a high-voltage amplifier (HVA), is applied to the PZT, adjustments to the optical grating will change the central wavelength of the ESL. The ESL beam passes through an optical isolator (OI) that prevents the damage from laser reflections. Then, the laser beam is split into two laser beams by a coupler (C1). One beam is routed to MZI1 to generate microwaves. These microwaves are monitored by a spectrum analyzer (SA). The second beam propagates through MZI2 and is used to control the linearity of the ESL modulation frequency sweep. A field-programmable gate array (FPGA) chip handles all signal-processing procedures and controls an analog-to-digital converter (ADC) to collect beat-frequency signals and then take fast Fourier transforms (FFTs) of it to analyze the variation in beat frequencies. If the variation exceeds the reference value, the FPGA will modify the ramp wave to assure the linearity of the frequency-modulated ESL.

The basic theory of this microwave generation system rests on the optical heterodyne concept and electronic feedback control [11,12]. We begin with the optical wave formula. The laser beam from the ESL is split by optical couplers (C1 and C2) and enters the MZI1 before passing to PD1. The optical fields of the two laser beams in MZI1 can be derived from

$$E_1 = A_1 \cos\left(\omega_1 t + \varphi_1\right) \tag{1}$$

and

$$E_2 = A_1 \cos\left[\left(\omega_1 - k\tau_1\right) t + \varphi_2\right], \tag{2}$$

where A_1 is the gain of the optical coupler, τ_1 is the optical delay-loop time of MZI1, k is the slope of the optical frequency sweep, ω_1 is the initial angular frequency, φ_1 and φ_2 are the phase angles of the two separated optical paths, respectively. When the two laser beams are received by PD1, the output of PD1 is given by

$$I_{PD1} = G_{PD} A_1^2 \cos\left[k\tau_1 t + \left(\varphi_1 - \varphi_2\right)\right]. \tag{3}$$

G_{PD} is the product of the optical power and responsivity of PD1 and $\left(\varphi_1 - \varphi_2\right)$ is a constant. We can simplify this constant as ϕ_1. Then Eq. (3) can be revised to state that

$$I_{PD1} = A_{PD1} \cos\left(k\tau_1 t + \phi_1\right), \tag{4}$$

where A_{PD1} is the total gain of MZI1. Then, in the case of MZI2, the signal has the same form,

$$I_{PD2} = A_{PD2} \cos\left(k\tau_2 t + \phi_2\right), \tag{5}$$

where τ_2 is a sufficiently small constant value in MZI2. Then, the beat-frequency signal from MZI2 is $\Delta\omega_2 = k\tau_2$. If $\Delta\omega_2$ remains constant, the slope of the optical-frequency sweep is also a constant. Thus, the ESL frequency modulation is linear.

3. System setup and experimental results

The microwave generation system is shown in Fig. 1. We select a Littrow-structure ESL with 10 kHz linewidth, containing an optical grating as a frequency-selecting component with 1050 grooves per mm and a central reflecting wavelength of approximately 1550 nm. When the first coupler C1 splits the frequency-modulated laser, 90 % of the beam enters MZI1 with the long ODL1, which has a 10-km-long polarization maintaining single-mode fiber (PM-SMF) with a refractive index of 1.448. This configuration yields a 48.93 μs delay time. The output of MZI1 will be received by photodetector PD1 (DET08CFC/M, Thorlabs Inc.), which has a 5 GHz bandwidth. The microwaves are formed on PD1, then encounter the electrical high-pass filter (HPF) to filter out the unexpected low-frequency noise, the HPF has the bandwidth from 1.4 GHz to 5.5 GHz. The filtered microwaves then enter spectral analyzer SA (RSA306B,Tektronix Inc.), which works at frequencies from 9 kHz to 6.2 GHz. Together, the HPF and the SA form a frequency monitor for assessing the output microwaves. The remaining 10% of the original beam of light passes through optical coupler C3, emerges as two equal beams, and enters MZI2 with ODL2, which is a 3-m-long PM-SMF with a refractive index of 1.448. This configuration yields a 14.48 ns optical delay time, sufficiently small to control the frequency modulation linearity. These two MZIs with all polarization maintaining components are placed in a sealed anti-vibration box to avoid environmental vibration which may introduces the phase noise. After passing through optical coupler C5, the laser output from MZI2 then enters the 1.2 GHz bandwidth photodetector PD2 (DET01CFC/M,