Microwave Photonics: Photonic Generation of Microwave and Millimeter-wave Signals

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Abstract- **Techniques to generate microwave and millimeter-wave (mm-wave) signals in the optical domain will be reviewed, with an emphasis on the techniques for microwave generation based on heterodyne of two phase correlated wavelengths.**

Index Terms- **Microwave photonics, photonic generation of microwave signals.**

I. INTRODUCTION

A low phase noise and frequency-tunable microwave or millimeter-wave (mm-wave) source is desirable for many applications such as in radar, wireless communications, software defined radio, and modern instrumentation. Conventionally, a microwave or mm-wave signal is generated based on electronic circuitry with many stages of frequency multiplication to achieve the desired frequency. The system is complicated and costly. In addition, for many applications, the generated microwave or mm-wave signal should be distributed to a remote site. The distribution of a microwave or mm-wave signal in the electrical domain is not practical due to the high loss associated with electrical distribution lines, such as coaxial cable. Thanks to the extremely broad bandwidth and low loss of the state-of-the-art optical fibers, the distribution of a microwave or mm-wave signal over optical fiber is an ideal solution to fulfill this task. Therefore, the ability to generate a microwave or mm-wave signal in the optical domain would allow the distribution of the signal over an optical fiber from a central office to a remote site, greatly simplifying the equipment requirement.

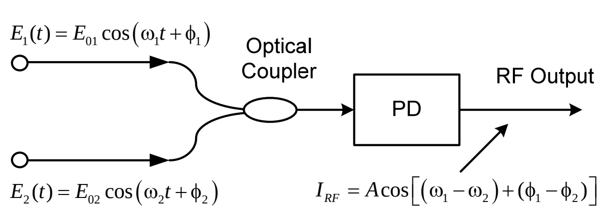


Fig. 1. Optical heterodyning of two optical waves to generate a microwave or mm-wave signal. PD: photodetector.

Usually, a microwave or mm-wave signal can be generated in the optical domain based on optical heterodyning, in which two optical waves of different wavelengths beat at a photodetector. An electrical beat note is then generated at the output of the photodetector with a frequency corresponding to the wavelength spacing of the two optical waves [1].

Assume that we have two optical waves given by

$$E_1(t) = E_{01}\cos\left(\omega_1 t + \phi_1\right), \quad (1)$$

$$E_2(t) = E_{02}\cos\left(\omega_2 t + \phi_2\right), \quad (2)$$

where E_{01}, E_{02} are the amplitude terms and ϕ_1, ϕ_2 are the phase terms of the two optical waves.

Considering the limited bandwidth of the photodetector, the current at the output of the photodetector is given by

$$I_{RF} = A\cos\left[\left(\omega_1 - \omega_2\right) + (\phi_1 - \phi_2)\right], \quad (3)$$

where A is a constant which is determined by E_{01}, E_{02} and the responsivity of the photodetector.

As can be seen from (3), an electrical signal with a frequency equal to the frequency difference of the two optical waves is generated. This technique is capable of generating an electrical signal with a frequency up to the THz band, limited only by the bandwidth of the photodetector. However, by beating two optical waves from two free-running laser sources would generate a microwave or mm-wave signal with high phase noise since the phase terms of the two optical waves are not correlated, which will be transferred to the generated microwave or mm-wave signal. Numerous techniques have been proposed and demonstrated in the last few years to generate low-phase-noise microwave or mm-wave signals with the two optical waves being locked in phase. These techniques can be classified into four categories: 1) Optical injection locking, 2) Optical phase-lock loop (OPLL), 3) Microwave generation using external modulation, and 4) Dual-wavelength laser source.

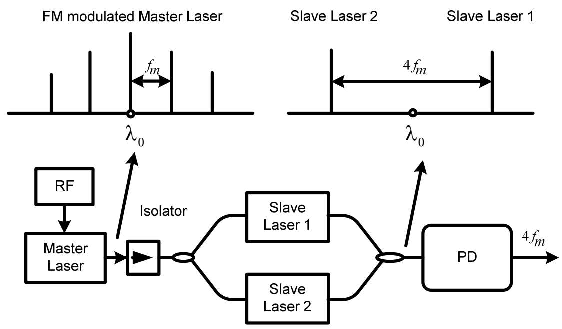


Fig. 2. Optical injection locking of two slave lasers. The master laser is directly modulated by a RF reference with its output injected into the two slave lasers. The slave lasers are wavelength-locked by the +2nd-order and -2nd-order sidebands from the output of the master laser.

II OPTICAL INJECTION LOCKING

To generate a high-quality microwave or mm-wave signal, the phase terms of the two optical waves used for heterodyning must be highly correlated. The phase coherence of two laser diodes can be realized by using optical injection locking [2]. Fig. 2 shows an optical injection locking system that consists of one master laser and two slave lasers. As can be seen an RF reference is applied to the master laser. Due to frequency modulation (FM) at the master laser, an optical carrier and different orders of optical sidebands are generated at the output of the master laser. The signal at the output of the master laser is then injected into the two slave lasers. The two slave lasers are selected such that their free-running wavelengths are close to two sidebands, say the +2nd and -2nd order sidebands in Fig. 2. Therefore, the wavelengths of the two slave lasers are locked to the +2nd and -2nd order sidebands, optical injection locking is thus achieved [2]. Since the two wavelengths from the two slave lasers are phase correlated, the beating of the two wavelengths at a photodetector would generate a beat note with low phase noise. In addition, depending on the design, the frequency of the beat note is equal to an integer multiple of the frequency of the RF reference applied to the master laser.

II. OPTICAL PHASE LOCK LOOP

Another approach to achieving phase correlation between two optical waves is to use an optical phase lock loop (OPLL), in which the phase of one laser is actively locked to that of a second laser by an OPLL, as shown in Fig. 3. This technique has been explored extensively in the past few years [3]-[9]. To achieve effective phase locking, the two lasers should be selected to have narrow line-widths and therefore have phase fluctuations only at low frequencies, which would ease significantly the requirement for a very short feedback loop.

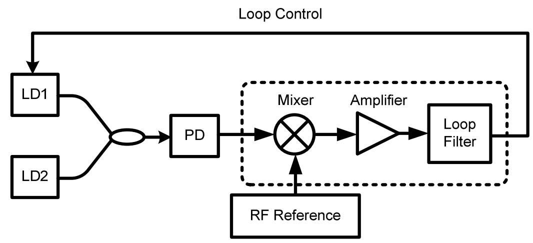


Fig. 3. Schematic of an optical phase lock loop. LD: laser diode. PD: photodetector.

As shown in Fig. 3, a beat note is generated at the output of the photodetector. The phase of the beat note is compared with that of an RF reference from a microwave generator at a mixer followed by a low-pass filter. The module in the dotted box is an electrical phase detector, with the output voltage being proportional to the phase difference between the beat note and the RF reference, which is an error voltage that is fed back to control the phase of one of the laser source by changing the laser cavity length or the injection current. With a proper feedback loop gain and response time, the relative phase fluctuations between the two lasers are significantly reduced and the phase of the beat note is locked to that of the RF reference.

To increase the frequency acquisition capability, a modified OPLL that incorporated a frequency discriminator was proposed [8]. It was demonstrated with the incorporation of the frequency discriminator, a pull-in range as large as 300 MHz was realized.

To reduce the feedback frequency, recently an OPLL incorporating a frequency down-conversion module was proposed and demonstrated [9]. The use of the frequency down-conversion module allows the use of lower-frequency components in the phase control module, which would reduce significantly the system cost. In addition, in a discriminator-aided OPLL, the use of the frequency down-conversion module would also allow the use of lower-frequency components in the frequency control module to reduce the system cost [9].

III. MICROWAVE GENERATION BASED ON EXTERNAL MODULATION

High-quality microwave signals can also be generated based on external modulation [10-13]. A method to generate an mm-wave signal using an external optical modulation technique was first proposed in 1992 [10]. A frequency-doubled electrical signal was optically generated by biasing the Mach–Zehnder modulator to suppress the even-order optical sidebands. A 36-GHz mm-wave signal was generated when the Mach-Zehnder modulator (MZM) was driven by an 18-GHz microwave signal. In 1994, another method was proposed to generate a frequency-quadrupled electrical signal. Instead of biasing the Mach–Zehnder modulator to suppress the even-order optical sidebands, the method [12] was based on the quadratic response of an optical intensity modulator. The optical carrier and the first and third-order optical sidebands were suppressed by adjusting the drive signal level. A 60-GHz millimeter-wave signal was generated when a 15-GHz drive signal was applied to the Mach–Zehnder modulator. However, to ensure a clean spectrum at the output of a photodetector, an imbalanced Mach-Zehnder filter with a free spectral range (FSR) equal to the spacing of the two second-order optical sidebands are used to suppress the unwanted optical components. Recently, an approach using an optical phase modulator to generate a frequency-quadrupled electrical signal was proposed [13]. In this approach, a Fabry-Perot filter was used to select the two second-order optical sidebands. An electrical signal that has four times the frequency of the electrical drive signal was generated by beating the two second-order sidebands at a photodetector. A key advantage of these approaches in [12] [13] is that an optical modulator with a maximum operating frequency of 15 GHz can generate a millimeter-wave signal up to 60 GHz. However, since both approaches rely on the optical filter to select the two optical sidebands, to generate a tunable mm-wave signal a tunable optical filter must be used, which increases significantly the complexity and the cost of the system.

For system applications with frequency reconfigurability, such as wideband surveillance radar, spread-spectrum or software-defined radio, a continuously tunable microwave or mm-wave signal is highly desirable. In [14] [15], two approaches to generating frequency tunable microwave signals using a MZM or a phase modulator incorporating a wavelength-fixed optical filter were demonstrated.

Fig. 4 shows a system to generate a continuously tunable mm-wave signal based on external modulation using a MZM and a wavelength-fixed optical filter [14]. The significance of the technique is that no tunable optical filter is required, which simplify significantly the system implementation.

As can be seen from Fig. 4, the system consists of a MZM that is biased at the maximum transmission point of the transfer function to suppress the odd-order optical sidebands. A fiber Bragg grating (FBG) serving as a wavelength-fixed notch filter is then used to filter out the optical carrier. A stable, low-phase noise mm-wave signal that has four times the frequency of the RF drive signal is generated at the output of the photodetector. In the experimental demonstration, a 32 to 50 GHz mm-wave signal was observed on an electrical spectrum analyzer when the electrical drive signal was tuned from 8 to 12.5 GHz. The quality of the generated mm-wave signal was maintained after transmission over a 25-km standard single-mode fiber.

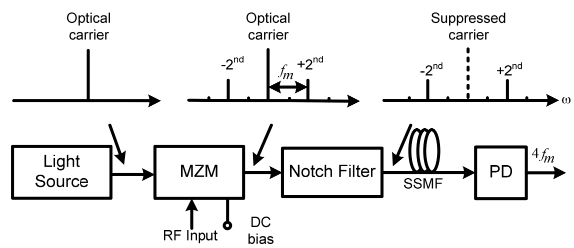


Fig. 4. Microwave signal generation based on external modulation using a Mach-Zehnder modulator and a wavelength-fixed optical filter. MZM: Mach-Zehnder modulator. PD: Photodetector.

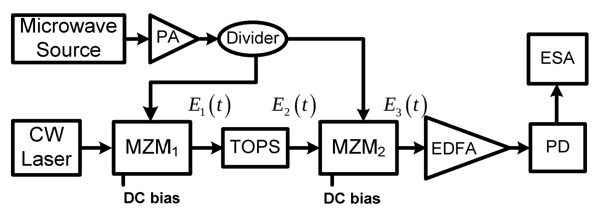


Fig. 5. Schematic diagram of the proposed microwave frequency octupling system using two cascaded MZMs. EDFA: erbium-doped fiber amplifier; ESA: electrical spectrum analyzer.

The technique in [14] [15] uses only a single MZM with a frequency multiplication factor of four. To generate a signal with a higher frequency, a higher multiplication factor may be needed. To do so, we may use two cascaded MZMs, with a multiplication factor of 6 or 8. Fig. 5 shows a system in which two MZMs that are biased at maximum transmission point to generate a frequency octupled microwave signal [16]. A detailed investigation of these techniques can be found in [17]. In addition to the use of an additional MZM, the use of a nonlinear device such as a length of nonlinear fiber or an optical semiconductor optical amplifier (SOA) cascaded with a MZM can also generate a microwave signal with a multifunction factor of six or twelve [18] [19].

IV. MICROWAVE GENERATION USING A DUAL-WAVELENGTH LASER

Microwave signals can also be generated using a dual wavelength laser source with the two wavelengths separated at a desired frequency [20]. It is different from the techniques of optical injection locking and the OPLL, the two wavelengths from a dual wavelength laser source are not locked in phase. However, due to the fact that the two wavelengths are generated from the same cavity, the phase correlation between the two wavelengths is better than that using two free-running laser sources. The advantage of using a dual-wavelength laser source to generate a microwave or mm-wave signal is that the system is simpler with no need for a microwave reference source, which can reduce significantly the system cost.

Fig. 6(a) shows a dual-wavelength fiber ring laser. To ensure that the two wavelengths are in single-longitudinal mode, a dual-band filter with ultra-narrow passbands must be used, to limit the number of longitudinal mode to be one in each passband. In the experimental demonstration, the ultra-narrow dual-band filter was a dual-wavelength ultra-narrow transmission band FBG with two ultra-narrow transmission bands, which was designed and fabricated based on the equivalent phase-shift (EPS) technique [21]. As can be seen from Fig. 6(b), the two ultra-narrow transmission bands of FBG1 are selected by the two reflection bands of FBG2, with the entire spectral response of the two cascaded FBGs shown in the lower figure of Fig. 6(b). Instead of using an EDFA in the ring cavity, a semiconductor optical amplifier (SOA) was employed as the gain medium. An SOA has less homogeneous line broadening at room temperature, the use of which would reduce significantly the mode competition of the two lasing wavelengths.

The key device was the ultra-narrow band FBG, which was fabricated based on the EPS technique [21]. It is different from the technique with a true phase shift, an equivalent phase-shift is introduced by changing the sampling period of a sampled FBG. In the fabrication of an EPS FBG, the fiber and the phase mask are both fixed, there are less phase fluctuations compared to the true phase shift method, in which the fiber or the phase mask must be laterally shiftable. In addition, the EPS can be controlled more precisely because it only requires a micrometer precision instead of nanometer precision for true phase shift during the FBG fabrication. Thus, an FBG with more precise phase shift leading to a much narrower transmission bandwidth is possible.

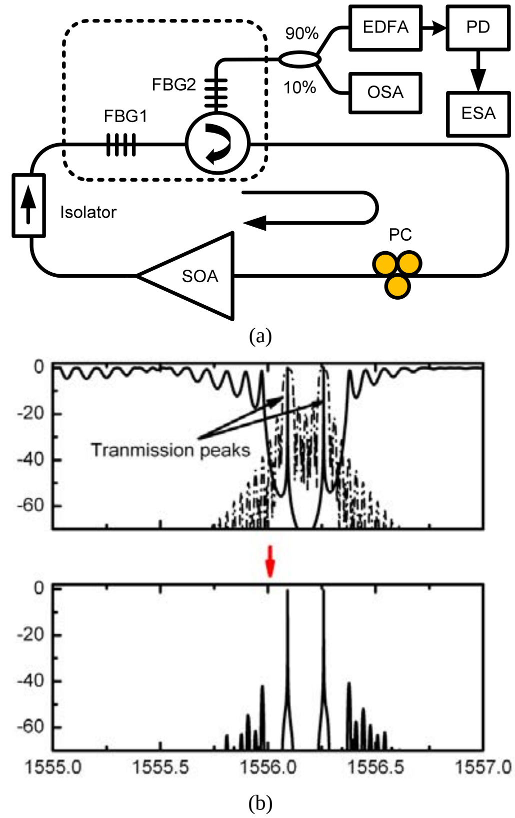


Fig. 6. A dual-wavelength single-longitudinal-mode fiber ring laser for microwave generation. (a) Schematic of the laser, (b) The spectral response of the two cascaded FBGs.

Since the two lasing wavelengths share the same gain cavity, the relative phase fluctuations between the two wavelengths are low. Three dual-wavelength ultra-narrow transmission-band FBGs with wavelength spacing of 0.148, 0.33, and 0.053 nm were incorporated into the laser cavity. Microwave signals at 18.68, 40.95, and 6.95 GHz were generated. The spectral width of the generated microwave signals as small as 80 kHz with frequency stability better than 1 MHz in the free-running mode at room temperature was obtained.

To avoid strong competition between the two wavelengths at room temperature, the gain medium in Fig. 6 is an SOA, since an SOA has less homogeneous line broadening as compared with an EDFA. However, a dual-wavelength fiber laser implemented based on an SOA has lower power and higher noise, with the optical noise contribute to the generated microwave when heterodyning at a photodetector. To increase the output power and reduce the noise, a solution is to use an EDFA. The key problem associated with the use of an EDFA is the strong homogeneous line broadening at room temperature which makes the two wavelengths to compete strongly with each other, leading to a very unstable operation. Recently, a dual-wavelength fiber laser implemented based on a sigma architecture that is composed of a ring loop and a linear standing wave arm was experimentally demonstrated [22]. Gain competition that prevents stable dual-wavelength oscillation is effectively suppressed by placing the gain medium in the standing-wave arm and by introducing polarization hole burning (PHB) via polarization multiplexing of the two lasing wavelengths in the ring loop, as shown in Fig. 7. The single frequency operation for each of the two wavelengths is guaranteed by an ultranarrow Fabry-Perot filter (FPF) introduced by absorption saturation in an unpumped erbium-doped fiber (EDF) and the gain saturation in the gain medium. In addition, the ring cavity forms a Lyot filter for each wavelength. Thus, wavelength switching is achieved by simply adjusting the polarization state of either wavelength. By beating the two SLM wavelengths at a photodetector, a microwave signal with a frequency tunable from ~10 to ~50 GHz is experimentally generated. Fig. 8(a) shows the spectrum of a generated microwave at 10 GHz. The electrical spectrum is shown in Fig. 8(b). The stability of the generated signal can be seen from the stable output at the generated electrical signal. The phase noise performance is shown in Fig. 8(c).

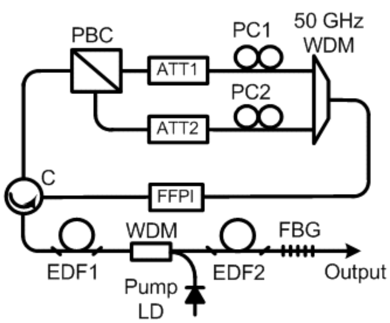
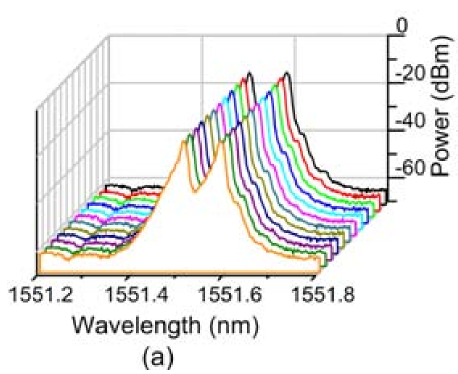
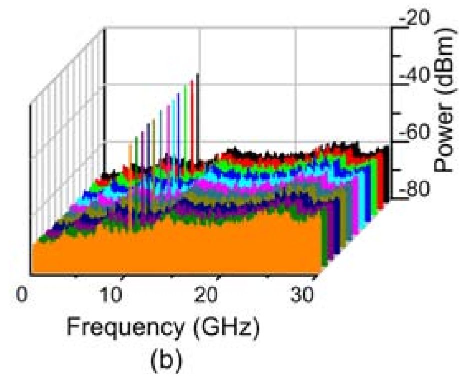


Fig. 7. A wavelength-switchable single-frequency dual-wavelength EDFA laser for microwave generation.





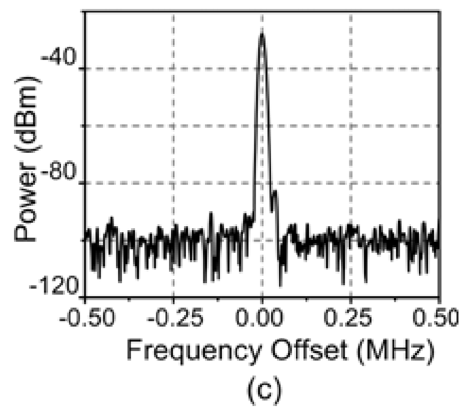


Fig. 8. Generation of 10-GHz microwave signal using the proposed fiber laser. (a) The optical spectra measured at a 3-min interval over a 36-min period; (b) the electrical spectra measured at a 3-min interval over a 36-min period, with RBW = 300 kHz; (c) the zoom-in view of the beating signal at SPAN = 1 MHz, RBW = 9.1 kHz.

The performance of the system shown in Fig. 7 was further improved by incorporating a high-finesse ring filter that was realized using a weakly pumped erbium-doped fiber in the ring. Thanks to the use of the high finesse ring filter, the side mode suppression ratio was greatly improved [23].

V. CONCLUSION

Microwave and mm-wave signals can be generated in the optical domain by heterodyning two wavelengths that are correlated in phase at a photodetector. Different techniques to achieve phase correlation have been proposed in the last few decades. In this paper, the techniques have been reviewed. In addition to the techniques discussed in this paper, there are other techniques to generate optically microwave signals, such as the microwave generation using an optoelectronic oscillator [24]. Microwave signals can also be generated based on optical pulse shaping [25], but the generated signals are usually pulsed. The key challenge in using the techniques for practical applications is the large size and high cost. The advancement in intergraded photonic circuits technologies would provide a potential solution to miniaturize the systems to reduced cost.

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