Dual-function Frequency and Doppler Shift Measurement System Using a Phase Modulator Incorporated Lyot Filter

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Abstract: *A microwave photonic dual-function system capable of measuring both instantaneous frequency and Doppler frequency shift is experimentally demonstrated. The system consists of a tunable Lyot loop filter that enhances spectral resolution and reduces measurement error.*

OCIS codes: (060.5625) Radio frequency photonics; (350.4010) Microwaves; (060.2420) Fibers, polarization-maintaining; (060.5060) Phase modulation.

1. Introduction

Instantaneous frequency measurement (IFM) and Doppler frequency shift (DFS) measurement systems are two essential tools in battlefield for identifying threats, providing electronic intelligence, and implementing deceptive countermeasures. Due to the advancement of emerging RF wireless systems, the frequencies that are encountered by IFM and DFS systems could range from MHz to tens of GHz, proposing a challenge to the electronic based measurement system. Photonics has been a promising solution to tackle challenges in modern RF electronic systems. Various microwave photonic based IFM systems and DFS measurement systems have been individually demonstrated. For example, IFM can be achieved using frequency-to-time mapping [1], power fading comparison [2][3], SBS-assisted phase-to-intensity modulation [4], and frequency-to-intensity mapping [5]. While DFS measurement systems can be achieved based on signal beating of sidebands generated from either cascaded intensity modulators [6] or the dual parallel MZMs [7]. Although existing photonic-based IFM and DFS systems solved some of the challenges in their electronic counterparts, they could easily suffer from low achievable resolution, narrow operation frequency range, as well as Doppler frequency shift measurement errors and significant resolution degradation in frequency measurement due to dynamic spectral misalignment.

In this paper, we propose and demonstrate a dual-function microwave photonic system that can perform both IFM and DFS measurements with adaptive and enhanced resolution as well as dynamic frequency measurement range. The proposed system can perform both IFM and DFS measurement without the need to replace any hardware, which provides operation flexibility when implementing it in a battlefield. The key component in our system is a phase modulator incorporated Lyot loop filter (PM-Lyot filter) [8] which is capable of fast adaptation to any spectral drifting as well as providing dynamic resolution setting based on the signal frequency. The PM-Lyot filter can be adjusted to achieve a sharp spectral profile with high peak-to-notch extinction ratio for the enhancement of frequency resolution and for a complete carrier suppression to ensure accurate DFS measurement.

2. Principle and Experimental Setup

Figure 1(a) shows the experimental setup of the proposed dual-function frequency measurement system. A distributed feedback laser (DFB) centered at 1549.03 nm is used as the optical carrier and the received RF signal at f_s is modulated onto the optical carrier through a 10-Gb/s electro-optic intensity modulator (IM). The IM is biased at its minimum transmission point to achieve carrier-suppressed double-sideband modulation (CS-DSB). The CS-DSB signal is then launched into the PM-Lyot filter. The PM-Lyot filter is an interferometric comb filter that consists of a pair of polarizers, a 10-Gb/s phase modulator (PM), a 9-m polarization maintaining fiber (PMF) and three polarization controllers (PC1-3). Free spectral range (FSR) Δf of the PM-LMF is governed by,

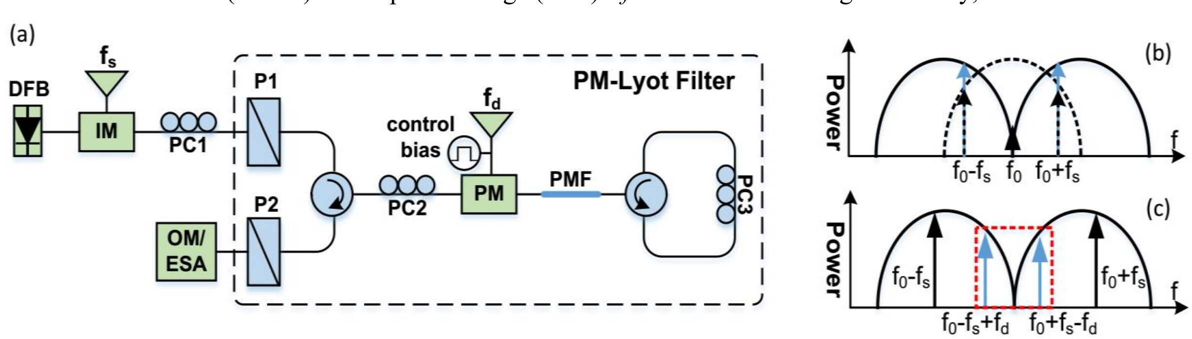

Fig. 1. (a) Experimental setup of the dual-function IFM and DFS system. DFB: distributed feedback laser; IM: Mach-Zehnder intensity modulator; PM: phase modulator; PMF: polarization maintaining fiber; PC1-3: polarization controller; P1-2: polarizer; OM: optical power meter; ESA: electrical spectrum analyzer. (b) Principle of IFM. (c) Principle of DFS measurement.

$$\Delta f = \frac{c}{B_{PMF} \cdot L_{eff} - B_{PM} \cdot L_{PM}} \quad (1)$$

where B_{PMF}, B_{PM}, L_{eff} and L_{PM} are the birefringence and effective length of the PMF and the waveguide in the phase modulator, respectively. The optical circulator and the polarization controller PC3 construct a loop that allows light to travel back to the PMF to experience additional birefringence. If the polarization rotation of PC3 is set to 0°, the light that is propagating back to the input will experience birefringence from the PM and PMF again, resulting in an effective length of $2L$. On the other hand, if PC3 is set to 45°, the light will not experience any birefringence on its way back (L_{eff}=L). In our experiment, the phase modulator consists of a 71-mm $LiNbO_3$ crystal with birefringence of 7.4×10^{-3} and a 1-m PMF pigtail at the output with birefringence of 3.0×10^{-4}, while the 9-m PMF has a birefringence of 6.33×10^{-4}. It is worth to notice that birefringence of the phase modulator waveguide can be slightly tuned by applying a DC bias voltage to it. The resultant change in FSR of the PM-Lyot filter is so small that only a spectral shift in the optical comb can be observed if we focus on a small wavelength section.

To perform IFM, the PM-Lyot filter transmission peak is first aligned with the optical carrier frequency (f_0) of the CS-DSB signal, such that the two sidebands (f_0-f_s and f_0+f_s) are aligned to the rising and falling slopes of the transmission function, as shown in Figure 1(b). Since the sidebands of signal with different frequency will align at a different part of the transmission function, different amount of optical power (P_{peak}= $\sin^2(\pi f_s/\Delta f)$) is resulted for different input frequency. However, the resultant optical power also depends on the input RF signal strength, meaning that any power fluctuation will negatively affect the accuracy of frequency measurement. To solve this problem, we propose to measure the power ratio of the sidebands between (i) P_{peak}: when the transmission peak is aligned with the carrier – dashed black curve and (ii) P_{notch}= $\cos^2(\pi f_s/\Delta f)$): when the transmission notch is aligned with the carrier –solid black curve. Tuning between the two cases is achieved by applying a DC voltage to the phase modulator, and fast tuning at tens of GHz is supported through electro-optics Pockel effect [9]. Power ratio between P_{peak} and P_{notch} always has a fixed relationship for certain frequency despite the power of the RF signal and the optical carrier. Thus, the frequency-to-power ratio (L_p in dB) can be expressed as,

$$L_p = \gamma \log[\tan\left(\frac{\pi f_s}{\Delta f}\right)] \quad (2)$$

where γ is proportional to the extinction ratio of the optical comb filter. When a higher frequency resolution is desired, the PM-Lyot filter can be tuned to have its FSR cut by half by setting polarization controller PC3 at 0°. On the other hand, if a larger frequency range is desired, the polarization controller PC3 is set at 45°, such that a full FSR is obtained to support doubling the frequency range.

Furthermore, the proposed system can be used for DFS measurement for advanced RF systems including satellite communication and missile radar where the carrier frequency is at GHz to tens of GHz. First, the transmitted signal f_s is modulated onto the intensity modulator to achieve CS-DSB modulation, while the received signal f_d (usually is tens of MHz from f_s) is modulated onto the sidebands f_0-f_s and f_0+f_s through a phase modulator and two sets of secondary sidebands f_0-f_s-f_d and f_0-f_s+f_d as well as f_0+f_s-f_d and f_0+f_s+f_d are generated, as illustrated in Figure 1(c). The PM-Lyot filter is having its transmission notch aligned with the optical carrier frequency such that the residue optical carrier of the CS-DSB signal can be completely suppressed to prevent errors in the measured Doppler frequency. Since the Doppler shift is typically below GHz range, a photodetector with bandwidth of 190 MHz is used to detect the beat signal between the two secondary sidebands, resulting in a beat signal frequency $f_b = 2|f_d - f_s|$. The factor 2 in the equation essentially enhanced the spectral resolution by two times.

3. Results and Discussion

First, we study the relationship between the spectral positions of the PM-Lyot filter with the bias voltage, as shown in Figure 2(a). The optical spectrum is measured by an optical spectrum analyzer (OSA) with 0.8-pm resolution. The PM-Lyot filter has a 21-dB extinction ratio and FSR of 0.493 nm, corresponding to 61.6 GHz in frequency. The comb shifts to a shorter wavelength while maintaining its overall profile when a positive DC bias is applied to the PM. A 1.6 V of voltage change is needed to shift the comb from peak to notch at a particular wavelength.

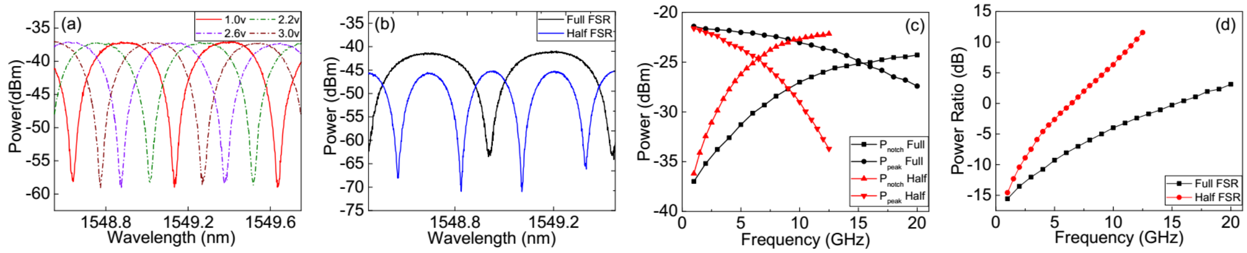

Fig. 2 (a) Transmission spectrum of PM-Lyot filter with different control bias at the PM; (b) Full FSR (black) and half FSR (blue) transmission spectrum resulted from the control feedback polarization; (c) P_{peak} and P_{notch} measurement when working at full FSR (black) and half FSR (red) settings; (d) Power ratio measurement when operating at full FSR (black) and half FSR (red) settings.

Furthermore, FSR of the PM-Lyot filter can be changed by controlling PC3 in the return loop. Figure 2(b) shows a half in FSR when PC3 is set at 0° (blue), and a full FSR with PC3 set at 45° (black). The red triangle and the black squares in Figure 2(c) show the direct power measurement of P_{peak} and P_{notch} when half and full FSR combs are used, respectively. The resultant power ratio L_p is shown in Figure 2(d) that clearly shows a 2.7-dB/GHz enhancement in frequency measurement resolution when half FSR setting is used instead of a full FSR setting.

Next, we use the proposed system for DFS measurement. The transmitted signal at 15 GHz is modulated onto an optical carrier using an intensity modulator to generate a CS-DSB signal, while the received signal is modulated onto the generated sidebands at the phase modulator in the PM-Lyot filter. Figure 3(a) shows the optical spectrum at the output of the PM-Lyot filter. For a clear display in Figure 3(a), a 14 GHz signal is used as the received signal instead to provide a significant spectral separation (2 GHz) between the two generated secondary sidebands. In Doppler frequency shift, the frequency difference should be in the order of kHz to MHz. Complete suppression of the optical carrier is observed as shown in the inset. Figure 3(b) and (c) show the resultant RF spectrum of Doppler shift measurement when the optical carrier is not completely removed, where incorrect frequency components are observed and causes error in the measurement. With the PM-Lyot filter, complete suppression of optical carrier is obtained and a pure frequency component is observed in Figure 3(d) and (e) - corresponds to two times of the Doppler frequency shift at 1 MHz and 100 kHz, respectively. Figure 3(f) and (g) shows the Doppler frequency shift spectrum with a smaller span, which indicate that a clear frequency tone is resulted from our DFS measurement.

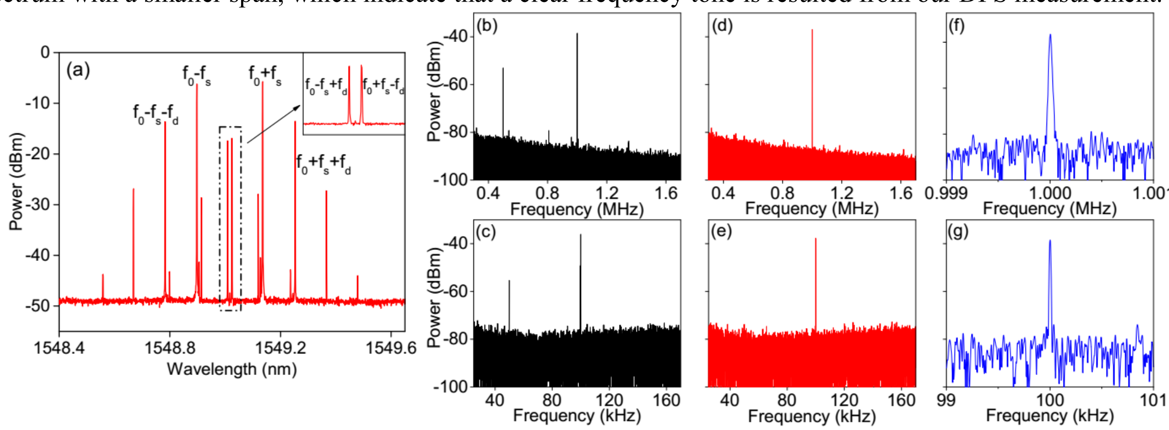

Fig. 3. (a) Optical spectrum of PM-Lyot filter output for Doppler shift measurment (inset: zoom-in view showing complete carrier suppression); (b)-(c) Measured DFS RF spectrum when carrier is not completely suppression; (d)-(e) Measured DFS RF spectrum when carrier is completely suppression (f)-(g) Zoom-in view that shows a clear single tone doppler frequency shifted spectrum.

4. Conclusion

A dual-function microwave photonic system that can measure both RF instantaneous frequency and Doppler frequency shift is experimentally demonstrated using a phase modulator incorporated Lyot loop filter. With the incorporation of phase modulator, dynamic adaptation to measurement range and resolution can be obtained. A 2.7 dB/GHz of resolution enhancement is achieved for frequency measurement. Complete carrier suppression is achieved to mitigate measurement error in Doppler frequency shift and to double the spectral resolution.

Acknowledgment

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