Photons-based wideband Doppler frequency shift measurement by in-phase and quadrature detection

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The authors propose and demonstrate a photonics-based wideband Doppler frequency shift (DFS) measurement scheme through in-phase and quadrature detection. The system has a compact structure applying cascaded phase modulation and polarisation modulation. It is easy to implement since both the value and sign of the DFS can be estimated by simple signal processing. More importantly, the proposed scheme is suitable for both DFS measurement and direction discrimination over a very wide frequency range. In the experiment, accurate DFS measurement with a large carrier frequency range from 5 to 40 GHz is demonstrated with the measurement error kept within \( \pm 12 \text{ Hz} \).

Introduction: Doppler frequency shift (DFS) measurement has important applications in wireless communications, electronic warfare, and radar systems [1]. In most of the cases, DFS estimation should have a wide operation frequency range up to tens of GHz, which is difficult to achieve by conventional electronic technologies due to the electrical bottleneck. To solve this problem, photonics-based DFS estimation is proposed with a large operation frequency range, which is realised by photonics-based microwave frequency mixing [2, 3]. Usually, in order to discriminate the moving direction of the target, additional tactics, such as applying a reference signal [2] or comparing the phase of two waveforms [3], are required to determine whether the DFS is positive or negative. In this Letter, we propose a compact scheme to implement wideband DFS measurement realised by photonics-based microwave in-phase and quadrature (I/Q) detection applying cascaded phase modulator (PM) and polarisation modulator (PolM). Thanks to the photonics frequency mixing mechanism, a wide operation frequency range can be achieved. Besides, the system can acquire both the value and sign of the DFS by simple digital signal processing (DSP) of the sampled complex signal after I/Q detection. Specifically, the value of the DFS is estimated by performing fast Fourier transformation (FFT) and the sign of the DFS is known by monitoring the phase change. Thus, the signal processing in the receiver is simplified compared with the previous demonstrations.

Principle: Fig. 1 shows the setup of the proposed DFS measurement system. The light from a laser diode (LD) is modulated by a PM, which is driven by a copy of the transmitted radar signal with a frequency of \( f_1 \). The optical field after phase modulation is

\[
E_a(t) = E_0 \cos[2\pi f_1 t + \beta_1 \cos(2\pi f_1 t)],
\]

(1)

where \( E_0 \) and \( f_1 \) is the amplitude and frequency of the optical carrier, respectively, and \( \beta_1 \) is the phase modulation index. This optical signal is sent to a PolM, which is a special PM that supports phase modulation along two principal axes with opposite phase modulation indices [4]. The PolM is driven by the echo signal having a frequency of \( f_1 \) and polarisation state of the incident light has an angle of 45° to one of the principal axes. After the PolM, the optical fields along the two principal axes (i.e., \( E_x \) and \( E_y \)) can be expressed as

\[
\begin{align*}
E_x &= \frac{1}{\sqrt{2}} \left[ \cos[2\pi f_1 t + \beta_1 \cos(2\pi f_1 t) + \beta_2 \cos(2\pi f_1 t + \varphi)] + \cos[2\pi f_1 t + \beta_1 \cos(2\pi f_1 t) - \beta_2 \cos(2\pi f_1 t)] \right], \\
E_y &= \frac{1}{\sqrt{2}} \left[ \cos[2\pi f_1 t + \beta_1 \cos(2\pi f_1 t) + \beta_2 \cos(2\pi f_1 t + \varphi)] - \cos[2\pi f_1 t + \beta_1 \cos(2\pi f_1 t) - \beta_2 \cos(2\pi f_1 t)] \right],
\end{align*}
\]

(2)

where \( \beta_2 \) is the modulation index of the PolM and \( \varphi \) is the phase difference between \( E_x \) and \( E_y \), which is set to \( \pi/2 \) by controlling by the dc-bias of the PolM. To boost the power, the optical signal can be amplified by an erbium-doped fibre amplifier (EDFA). An optical bandpass filter (OBPF) is followed to select the first or the -1st-order sidebands generated by phase modulation and polarisation modulation. When the -1st-order sidebands are selected, the obtained optical fields are

\[
\begin{align*}
E_{x_1} &= \frac{1}{\sqrt{2}} \left[ J_0(\beta_1)J_1(\beta_2) \cos[2\pi f_1 (f_c - f_0)t] + J_0(\beta_1)J_1(\beta_2) \cos[2\pi f_1 (f_c - f_0)t - \pi/4] \right] \\
E_{y_1} &= \frac{1}{\sqrt{2}} \left[ J_0(\beta_1)J_1(\beta_2) \sin[2\pi f_1 (f_c - f_0)t] - J_0(\beta_1)J_1(\beta_2) \sin[2\pi f_1 (f_c - f_0)t + \pi/4] \right]
\end{align*}
\]

(3)

where \( J_n \) is the nth order of the first kind of Bessel function. This optical signal is split into two branches by a splitter. In each branch, a polariser (Pol) is applied to extract the optical signal along the polarisation direction that has an angle of \( \alpha \) to one of the principal axes of the PolM. The obtained signal can be expressed as

\[
E_b(t) = \alpha E_x - E_y.
\]

(4)

In the upper branch, \( \alpha \) is chosen as 90°. The optical signal after Pol is

\[
E_b(t) = \alpha J_0(\beta_1)J_1(\beta_2) \sin[2\pi f_1 (f_c - f_0)t] - J_0(\beta_1)J_1(\beta_2) \sin[2\pi f_1 (f_c - f_0)t].
\]

(5)

In the lower branch, \( \alpha \) is set to 45°. The obtained signal after Pol2 is

\[
E_b(t) = \alpha J_0(\beta_1)J_1(\beta_2) \cos[2\pi f_1 (f_c - f_0)t - \pi/2] + J_0(\beta_1)J_1(\beta_2) \cos[2\pi f_1 (f_c - f_0)t + \pi/2].
\]

(6)

Then, the optical signal after each polariser is sent to a photo-detector (PD) for square-law detection. The dc components of the obtained two electrical signals are eliminated by a dc block, respectively. The ac parts of the electrical signals in the upper and lower branches are given as

\[
\begin{align*}
&\nu_0(t) \approx \alpha J_0(\beta_1)J_1(\beta_2) \sin[2\pi f_1 (f_c - f_0)t], \\
&\nu_0(t) \approx -\alpha J_0(\beta_1)J_1(\beta_2) \sin[2\pi f_1 (f_c - f_0)t].
\end{align*}
\]

(7)

As can be seen, two IF signals with a phase difference of 90° are obtained, indicating the photonics-based I/Q detection is implemented. After sampling the electrical signals in the two branches with a two-channel ADC, a complex signal of the transmitted signal is set to be 20 GHz and the echo signal is at 100 kHz. The optical spectra of the transmitted signal is included in Fig. 2, where the spectral response of the OBPF is also included.

Fig. 1 Setup of proposed DFS measurement system. LD: laser diode; PM: phase-modulator; PolM: polarisation modulator; OBPF: optical band-pass filter; Pol: polariser; PD: photo-detector.

Experimental demonstration: An experiment is carried out based on the setup in Fig. 1. An LD (TeraXion) with a wavelength of 1550.12 nm and an output power of 16 dBm is used as the light source. It is modulated by a PM (EOSpace AZ-AV5-40) with a bandwidth of 40 GHz. The PM is driven by the transmitted signal generated by a microwave signal generator (Keysight, E8257D). The echo signal generated by another tunable microwave signal generator (Keysight, ES267D) is applied to drive the PolM (Versawave Inc.) having a bandwidth of 40 GHz. After the PolM, an EDFA (Amonics Inc.) is used to boost the optical power and an OBPF (Yenista, XTM-50/S) is followed to select the -1st-order modulation sidebands. The output signal from the OBPF is split into two branches by an optical coupler. In each branch, a polarisation controller and a polarisation beam splitter are used as a polariser, and a PD (Discovery Semiconductors, DSC505) having a bandwidth of 12 GHz and a responsivity of 0.80 A/W is used to implement optical-to-electrical conversion. After passing through a dc block, respectively, the obtained two electrical signals are sampled and recorded by using a real-time oscilloscope (Keysight, DSO-X 92504A).

First of all, feasibility of the proposed method is tested. The frequency of the transmitted signal is set to be 20 GHz and the echo signal is at 19.9999 GHz. In this case, the DFS is \(-100 \text{ kHz}\). The optical spectra of the signals at the outputs of the PM, the PolM and the OBPF are measured, respectively, using an optical spectrum analyser, as shown in Fig. 2, where the spectral response of the OBPF is also included. Fig. 3a shows the waveforms of \( \nu_0(t) \) and \( \nu_0(t) \), sampled by using the real-time oscilloscope with a sampling rate of 1 Msa/s. Two side-outputs are off phase by 90°, in agreement with the I/Q detection property. The spectrum obtained by performing FFT to \( S(t) \) in a period of 1 s.
is shown in Fig. 3b, where the unwrapped phase of 50 complex signal samples is shown in the inset. The maximum frequency component in Fig. 3b is found to be 100.002 kHz, thus the estimated DFS value is 100.002 kHz and the measurement error is 2 Hz. Here, the DFS measurement resolution is 1 Hz, which is determined by the length of the digital samples used for FFT calculation. In Fig. 3b, the increasing phase shown in the inset indicates the DFS is negative and the target is receding from the receiver. When the frequency of the echo signal is changed to 20.0001 GHz, the sampled waveforms of $v_\phi(t)$ and $v_d(t)$ are shown in Fig. 3c. The spectrum and unwrapped phase of $S(t)$ are shown in Fig. 3d. The DFS value is estimated to be 100.005 kHz and the measurement error is 5 Hz. The decreasing phase indicates the DFS is positive and the target is approaching towards the receiver. These results can verify the proposed DFS measurement technique is feasible.

![Fig. 2 Measured optical spectra of output signals from PM, PolM, and OBPF (response of OBPF is also included)](image)

![Fig. 3 Sampled signal analysis](image)

The prominent advantage of the proposed method is that it can work in a wide frequency range. To validate this property, a series of transmitted frequencies at 5, 10, 20, 30, and 40 GHz are tested. The echo signals are set to be 1, 5, 10, 50, 100, 500, and 1000 kHz lower and higher than the transmitted signal. The sampling rate of the oscilloscope is 1 MHz. Thanks to the photonics-based I/Q detector composed by a PM, a PolM, and two polarizers, the system is capable of performing accurate DFS measurement in a wide frequency range without direction ambiguity. In the experiment, the established system can estimate the DFS in a wide frequency range from 5 to 40 GHz. The measurement errors are kept within ±12 Hz.

**Conclusion:** A photonics-based wideband DFS measurement system based on I/Q detection is proposed and demonstrated. Thanks to the photonics-based I/Q detector composed by a PM, a PolM, and two polarizers, the system is capable of performing accurate DFS measurement in a wide frequency range without direction ambiguity. In the experiment, the established system can estimate the DFS in a wide frequency range from 5 to 40 GHz. The measurement errors are kept within ±12 Hz.

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