Fast optical frequency detection techniques for coherent distributed sensing and communication systems

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Abstract: We present techniques for detecting fast optical frequency variations with high spectral resolution for coherent detection based distributed sensing and communication systems, for which conventional spectral measurement techniques cannot meet the speed and spectral resolution requirements.

1. Introduction

Coherent distributed optical sensing systems, such as FMCW Lidar, optical coherence tomography (OCT), and optical frequency domain reflectometer (OFDR), generally require a frequency tunable laser scanning at high speed. Ideally, the laser frequency tuning should be linear in order to obtain the best spatial resolution. Unfortunately, in reality, almost all tunable lasers have certain tuning nonlinearity. In addition, some lasers may have frequency noises causing local tuning direction reversal. In order to minimize the negative impact of the scan nonlinearity, unbalanced Mach-Zehnder interferometers are often used to get the k-clock or the frequency clock (f-clock) by relating the times at the zero-crossings of the interference signal to the optical frequency increments. In particular, whenever the interference signal crosses the zero, a frequency increment equal to the free spectral range (FSR) of the interferometer is obtained, as shown in Fig. 1(a). Such a method suffers from two major drawbacks. First, it assumes that the optical frequency changes monotonically during the scan, which may result in wrong frequency measurement whenever a local frequency reversal occurs around a zero-crossing due to the laser frequency noises. Second, for long range sensing requiring high frequency resolution, the fiber delay required in the unbalanced Mach-Zehnder interferometer is very long, on the order of hundred meters or more, which make it difficult to miniaturize the system with integrated photonics. In addition, the method only measures incremental frequency changes and no information on the absolute frequency of wavelength of the laser can be obtained.

Wavemeters [1,2] based on Fizeau interferometer, scanning Michelson interferometer, and Fabry-Perot interferometer can be used to precisely measure laser frequency variations. However, their measurement speed and frequency resolution are generally not sufficient for the demanding distributed sensing applications, although they have exceptionally high wavelength measurement accuracies. For optical spectrum analyzers (OSAs) [3] relying on diffractive gratings or tunable narrow-band filters, the resolution, spectral range, and measurement speed generally counter play with one another [4], and therefore good performances of all three parameters cannot be achieved simultaneously, although they are required for coherent distributed sensing applications.

For coherent distributed sensing applications, it is important to know the following transient characteristics of the tunable lasers: the frequency scan rate, nonlinearity, range, and repeatability, in addition to the power variation and frequency jitter during each scan. For telecom coherent detection and distributed acoustic sensing (DAS) systems, fast detection of the frequency jitter of the narrow band DFB lasers is also desirable, with which it is possible to reduce the jitter via feedback or compensate for the jitter effect.

We previously reported a polarimter based optical frequency analyzer [4] which is capable of detecting optical frequency with high speed, high resolution and large range, simultaneously. In this paper, we focus our latest work on sine-cosine optical frequency detector, which is a much simplified version of our previous work.

2. The description of the sine-cosine optical frequency detector

Fig. 1(b) shows a prior polarimter based optical frequency detector [4] in which a light beam passes through a differential group delay (DGD) or a birefringence crystal before being detected by a high speed polarimter. The light is linearly polarized 45º from the slow axis of the DGD element so that it has equal amplitude along the slow and fast axes. Consequently, when the frequency of light scans, the state of polarization (SOP) traces out a large circle on the Poincare Sphere, as shown in Fig. 1(b). The angle of SOP variation $\Delta\theta$ in the plane of the large circle in response to a frequency variation Δf is $\Delta\theta = 2\pi\Delta f\tau$, where τ is the relative group delay between the slow and fast polarization components in the birefringence crystal. Therefore a frequency increment can be easily obtained if τ is known.

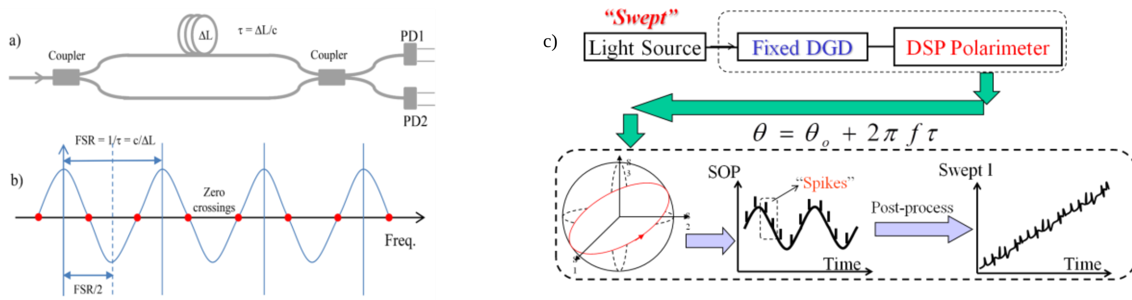

Fig. 1. (a) Mach-Zehnder interferometer for incremental frequency measurement. (b) Zero-crossings are used to determine the frequency increment equal to the free spectral range. c) A polarimeter based optical frequency detector.

The configuration of Fig. 1(b) is sensitive to the input polarization and requires a Stokes polarimter with complicated data processing which compromises the detection speed. Fig. 2(a) illustrates a new configuration which overcomes the drawbacks above [5]. The input beam of an arbitrary polarization first enters a polarization displacer made with a birefringence crystal in which the two beams 1 and 2 with the orthogonal polarization components are displaced. A 90º polarization rotator is then placed in one of the beam to make the two beams having the same polarization state. Polarizer 1 oriented 45º from the slow axis of the DGD element is used to clean up the polarization deviation from the imperfections of the polarization rotator made of either a half-wave plate or a Faraday rotator, as shown in Fig. 2(b). Quarter wave plate is oriented parallel or anti-parallel with the DGD element. All other polarizers are oriented the same as polarizer 1. A lens with a properly selected focal length is used to focus two beams onto two photodetectors. Fig. 2(c) shows the SOP tracing out a circle on in the (s_2,s_3) plane as the optical frequency scans. The variation of the optical frequency can be obtained from the photo voltages below:

$$cos\Delta\theta = (V_{1x} - V_{1y})/(V_{1x} + V_{1y}) \quad (1a)$$

$$sin\Delta\theta = (V_{2x} - V_{2y})/(V_{2x} + V_{2y}) \quad (1b)$$

$$\Delta f = \frac{1}{2\pi\tau}\Delta\theta = \frac{1}{2\pi\tau}\tan^{-1}\frac{(V_{2x}-V_{2y})/(V_{2x}+V_{2y})}{(V_{1x}-V_{1y})/(V_{1x}+V_{1y})}, \quad (1c)$$

where V_{1x}, V_{1y}, V_{2x}, and V_{2y} are the photo voltages detected by PD1, PD2, PD3, and PD4, respectively. It is important to notice that the optical frequency variation can be represented as sine and cosine functions of the detected signals and therefore one can obtain both the magnitude and direction of the frequency change with endless range without ambiguity, similar to a sine-cosine or quadrature decoder for a motor.

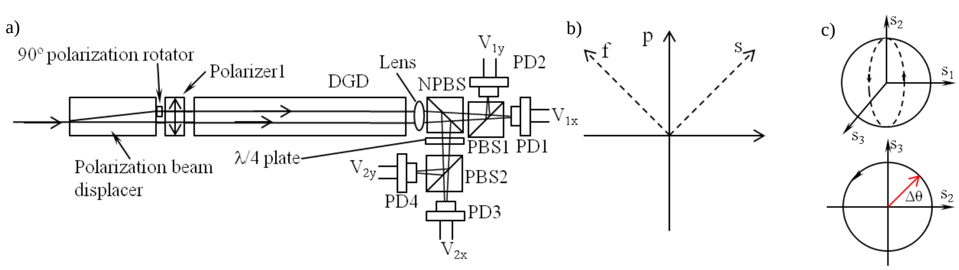

Fig. 2. Illustration of a sine-cosine optical frequency detector. (a) The optical configuration. (b) The SOP direction in relation to the crystal axes. (c) The trajectory of the SOP on the Poincaré Sphere. NPBS: polarization insensitve beam splitter, PBS: polarization beam splitter, PD: photodetector.

3. Experimental results

With a DGD of only 2.7 ps (0.8 mm), we achieve a frequency resolution of less than 10 MHz (0.1 pm). Fig. 3(a) shows the measured instantaneous frequency (top) of a tunable laser module around 1550 nm (Pure Photonics) and the corresponding tuning rate (bottom) using the sine-cosine optical frequency detector (OPD) of Fig. 2. The tuning nonlinearity can be clearly detected. Fig. 3(b) shows the measured wavelength of a Yenista tunable laser as a function of time (blue) and the digitally generated k-clock of equal frequency spacing. Any k-clock spacing can be generated using the embedded FPGA circuit in the OPD module.

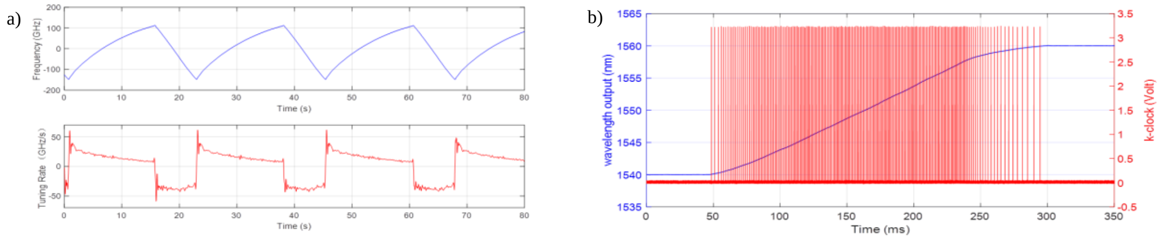

Fig. 3. a) Measured optical frequency of a tunable laser module (top) and its tuning rate (bottom). b) Measured wavelength ramp of a tunable laser (blue) and digitally generated k-clock.

Fig. 4(a) shows the measured instantaneous frequency (blue) of an OCT laser (Thorlabs) operating at 8 kHz repetition rate with a wavelength scanning range of 115 nm, with the red line showing the linear fit and green line the sinusoidal fit. Fig. 4(b) shows the frequency ramp of another OCT laser (Thorlabs) at 100 kHz repetition rate with a range of 110 nm. For analyzing the scan nonlinearity, we calculated the deviations of the measured frequency from the linear and sinusoidal fits, as shown in Figs. 4(c) and 4(d), respectively. In Figs. 4(a) and 4(b), the measured blue lines can be hardly seen because they are buried in the fitting curves of red and green lines.

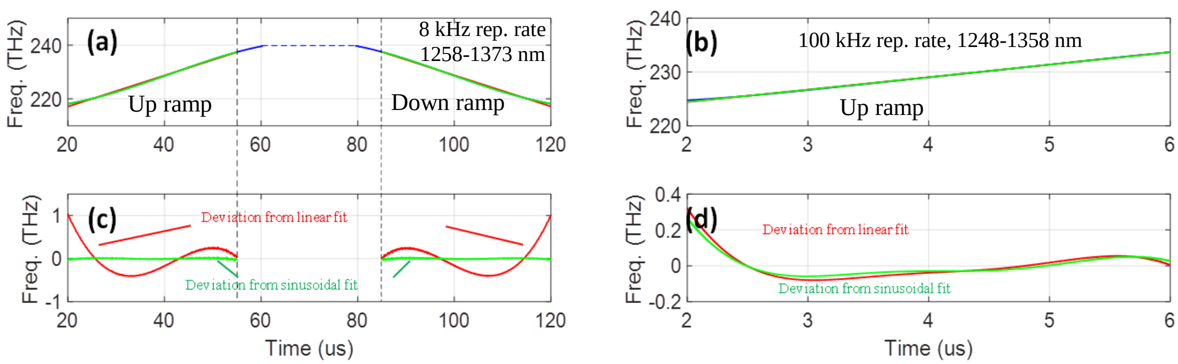

Fig. 4. Instantaneous optical frequency of OCT lasers at 8 kHz (a) and 100 kHz (b) repetition rates, respectively. (c) and (d): the corresponding nonlinearity represented by deviations from linear and sinusoidal fits for (a) and (b) respectively. The dash line in the center of (a) indicates that the optical power dropped to nearly zero.

In summary, we review different techniques for measuring the instantaneous optical frequency of tunable lasers, focusing on the sine-cosine optical frequency detector we developed for accurately measuring different tunable lasers for coherent distributed sensing applications (OCT, OFDR, and FMCW Lidar). We will also present techniques and data for frequency jitter measurements of fixed frequency lasers for telecom coherent detection and distributed acoustic sensing (DAS) systems at the presentation.

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5. References

1. J. L. Hall and J. L. Carlsen, Eds., *Laser Spectroscopy III* (Springer-Verlag, Berlin, 1977);
2. J. J. Snyder, "Laser Wavelength Meters," Laser Focus 18, 55 (1982).
3. D. Derickson, "Fiber optic test and measurement," (Prentice Hall, 1998.), chap. 3.
4. X. Steve Yao1, B. Zhang, X. Chen, and A. Willner, "Real-time optical spectrum analysis of a light source using a polarimeter", Opt. Express, 16 (22), 17854-17863 (2008).
5. X. Steve Yao et al, "Sine-cosine optical frequency encoder devices based on optical polarization properties," US patent 10895477 (2021).