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Nonuniform Microwave Photonic Delay-Line Filter For Optical Sensor Network Interrogation

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***Abstract*—We propose a new design of nonuniform spaced microwave photonic delay-line filter based generic optical fiber sensors interrogation platform. Both the amplitude and phase response of the microwave filter are used to demodulate optical sensors. Therefore, a large sensor network with different types of optical sensors can be interrogated simultaneously. The concept of this new microwave photonics enabled interrogation approach is presented and verified by simulations where four different types of optical sensors are simultaneously interrogated via inverse Fourier transform of filter frequency response.**

Keywords—microwave photonics, finite impulse response, time delay, Fourier transform, fiber Bragg grating, optical sensors

I. INTRODUCTION

Microwave photonic research has been dominantly focused on the use of photonic techniques for generation, distribution, control, detection and processing of high-frequency microwave signals [1]. This is due to the unique advantages offered by optical methods compared to its electrical counterpart, including the extremely wide bandwidth, high speed, improved flexibility and inherent immunity to electromagnetic interference. On the other hand, microwave photonic techniques have also shown promising contributions in improving the performance of optical sensing systems [2, 3]. As the sensing information carried by optical signals can be converted to the microwave domain, the interrogation speed and resolution can be significantly enhanced thanks to mature microwave testing method.

Microwave photonics based optical sensor interrogation has attracted ever increasing interest in the past a few years. For example, by converting the change of optical wavelength to the temporal shift of a microwave waveform based on photonic time stretch (PTS) concept, interrogation speed of fiber Bragg grating (FBG) sensors has been increased to MHz range [4, 5]. Furthermore, by exploiting the unique wavelength-location mapping in a chirped FBG, high-resolution fully distributed FBG sensor interrogation can be achieved via instantaneous microwave frequency sensing [6]. Another microwave photonic technique that has attracted great attention for high-speed and high resolution optical sensing is optoelectronic oscillator (OEO) [7, 8]. In the OEO-based sensor interrogation scheme, the measurand information is carried by an optical filtering device, which in turn determines the high-quality microwave oscillation frequency. The change of optical domain resonance wavelength is translated to RF frequency change thus offering high-speed and high-resolution sensor interrogation.

Microwave photonic filter (MPF) is one of the key elements in microwave photonic systems, which normally uses delayed multi-tap optical signals carrying a microwave signal to form the desired filter response [9]. Based on the same motivation as in PTS- and OEO-based systems, the use of finite impulse response (FIR) microwave photonic delay-line filters for optical sensing applications has gained ever increasing interest recently [3]. The principle concept is that the targeted sensing information is converted to optical delays between different filter taps and can be interrogated via variation of the microwave photonic filter response. For example, a transverse load sensor [10], a fiber length sensor [3], and a temperature sensor [11] have been successfully interrogated with high-resolution via a microwave photonic delay line filter. However, as uniformly spaced microwave photonic linear-phase filters are used in these systems, the measurand information is usually demodulated from the change of free spectral range (FSR) of the filter. Thus only one sensor or two sensors (both temperature and loading) [12] can be interrogated using a microwave photonic delay-line filter setup. A quasi-distributed hot-spot event detection system involving multiple optical sensors has been implemented using a microwave photonic filter [13]. However, all the sensors are of the same type. More complicated microwave photonic filter structure would be required to measure different types of optical sensors. Therefore, a new microwave photonic filter based optical sensor interrogation scheme with the capability of measuring an optical sensor network with a large number of sensors of different types is highly demanded.

In this work, we propose and demonstrate a new design of generic optical sensor network interrogation platform based on a nonuniformly spaced microwave photonics delay-line filter with nonlinear phase response. The amplitude and time delay of each filter tap can be individually modulated by different types of optical sensors embedded in filter taps. As both amplitude and phase response of the filter are used to

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decode the measurand information, multiple optical sensors of different types can be interrogated simultaneously from the temporal impulse response of the microwave photonic filter. This new design holds great potential in microwave photonics enabled high-resolution and large-scale optical sensor network interrogation.

II. PRINCIPLE

A typical delay line microwave photonic FIR filter is built on multiple weighted and delayed optical signals carrying the same microwave signal. When combining multiple delayed copies of the input microwave signal after photodetection, the power and phase of the recovered microwave signal depend on the signal frequency. Therefore, a desired microwave filter response can be formed by controlling the filter taps [9]. If optical sensors are embedded in filter taps, they can be interrogated via inverse Fourier transform of the microwave filter response [3]. In most existing systems [10-12], a uniformly spaced linear-phase microwave photonic filter is always assumed. The optical sensors are interrogated from the change of FSR of the microwave photonic filter. Therefore, only limited number of sensors or multiple sensors of the same type can be measured.

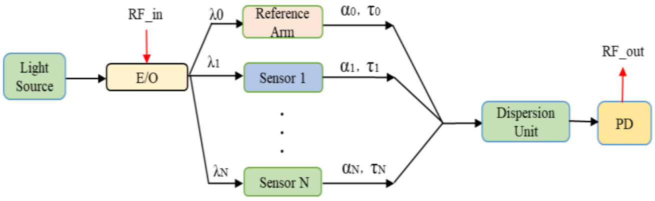

Fig. 1. Schematic diagram of the proposed optical sensor interrogation network based on a nonuniform microwave photonic delay line filter.

Fig. 1 shows the structure of the proposed nonuniform microwave photonic delay line filter based optical sensor network interrogation system. It can be seen that multiple optical sensors of different types are included in all filter taps except the first one, which functions as the reference arm for the whole network. The frequency response of the delay-line microwave photonic filter is given by [9]

$$H(\Omega) = \sum_{k=0}^{N-1} \alpha_k e^{-j\Omega\tau_k} \tag{1}$$

where Ω is the angular microwave frequency, N is the total number of filter taps, α_k and τ_k are the amplitude and time delay of the k^{th} tap, respectively. Optical sensors in each arm will modulate the amplitude and time delay of the filter taps. A nonuniformly spaced microwave photonic delay line filter [14] will be formed. As a result, the amplitude response of the filter will not have periodic patterns with fixed FSR as in normal delay-line filters, and the phase response is not linear anymore. More parameters other than only the FSR can be used to demodulate the sensors embedded in the filter arms.

Here both the amplitude and phase response of the filter are used. Therefore, all the optical sensors can be individually interrogated via inverse Fourier transform of the complete frequency response of the nonuniform microwave photonic filter. More importantly, different types of optical sensors can be measured as long as they can change the power of optical signal through attenuation or slope edge filtering, or change the time delay in the filter tap through optical length change or wavelength shift with the help of chromatic dispersion in the system.

III. RESULTS

The proposed design is verified by simulations. The nonuniformly spaced delay line filter is configured using an incoherent broadband optical source, as shown in Fig. 2. Filter taps are formed based on spectrum slicing using narrow-band uniform fiber Bragg gratings (FBGs) in each filter arms [15]. Some of the FBGs are spectral filtering device only and other are functioning as optical sensors as well. The use of broadband source enables interrogation of multiple wavelength modulated optical sensors, such as FBG sensors, with large measurement range.

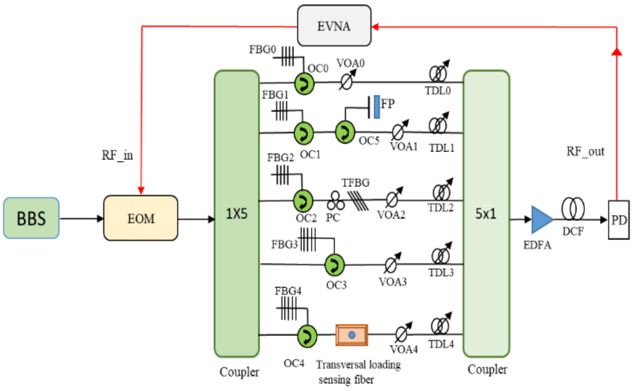

Fig. 2. An example of nonuniformly spaced microwave photonic delay-line filter with give taps for interrogation of different types of optical sensors. BBS: broadband source; EOM: electro-optical modulator; OC: optical circulator; FP: Fabry-Perot cavity; EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; TDL: tunable delay line; PC: poloarization controller; TFBG: tilted fiber Bragg grating; DCF: dispersion compensating fibr; PD: photodetector; EVNA: electrical vector network analyzer.

In this example, a delay-line microwave photonic filter with five taps is considered. Five uniform FBGs with equal reflection bandwidth of 0.5 nm are included in each filter tap to slice the broadband optical spectrum. The first filter tap serves as the reference arm, where FBG0's reflection and central wavelength always keep constant. The other four filter taps are the sensing arms, where four different optical sensors are incorporated. Variable optical attenuators (VOAs) and tunable time delay lines (TDLs) are included in all the filter arms for calibration purpose. For example, the delay-line filter can be configured to have five equally weighted and uniformly delayed filter taps before any sensing information is added.

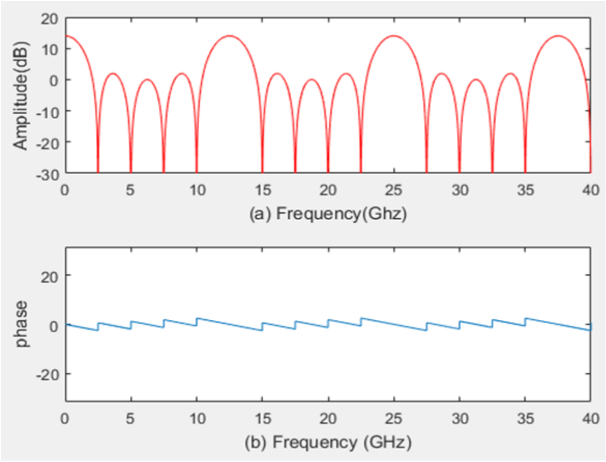

Fig. 3. Frequency response of a calibrated five-tap uniformly spaced microwave photonic delay-line filter.

Figure 3 shows frequency response of the resultant five-tap uniformly spaced microwave photonic delay-line filter, where the time delay between filter taps is 80 ps. Once the optical sensors change the amplitude and time delay of filter taps, the filter will become a nonuniformly spaced microwave photonics. Our proposed design supports interrogation of a large sensor network. Here for illustration purpose, four different types of optical sensors are considered.

The first sensor in the second filter arm is a Fabry-Perot (FP) cavity based refractive index sensor [16]. When the refractive index of a solution is changed, the optical spectral oscillation response will be shifted due to the slight change in FSR. As the central wavelength of the FBG filter in this arm is fixed, only the overall optical power will be changed due to slope filtering at the FP cavity and time delay of this tap will remain the same. Taking parameters from [16], we set the sensitivity of the refractive index induced power change as 0.66/0.01RIU.

The second sensor is a tilted fiber grating (TFG) based twist sensor [17]. The twist angle of the TFG sensor can be demodulated from the wavelength shift of the wideband notch filter in the transmission spectrum. Again, this wavelength shift will be converted to optical power change only as the central wavelength of the FBG in this arm is also fixed. According to [17], the measurement sensitivity is set as 0.08 per degree.

The third sensor is a FBG-based lateral pressure sensor [18]. Here the FBG3 is not only working as the narrow-band filter for spectrum slicing, but also as the optical sensor to measure the lateral pressure added to the fiber. FBG-based pressure sensor is wavelength-modulated. Therefore, only the time delay will be change for this filter tap. According to [18], we set the pressure measurement sensitivity as 36 nm/MPa.

The last filter tap involves two optical sensors: a FBG sensor to measure the temperature change and an optical fiber sensor to measure the transverse loading [19]. The FBG sensor is wavelength modulated and loading sensor is attenuation (power) modulated. Therefore, both amplitude and time delay of this filter tap will be changed. Based on the results from [19], we set the measurement sensitivity of the two sensors as 0.2/g and 0.026nm/℃, respectively.

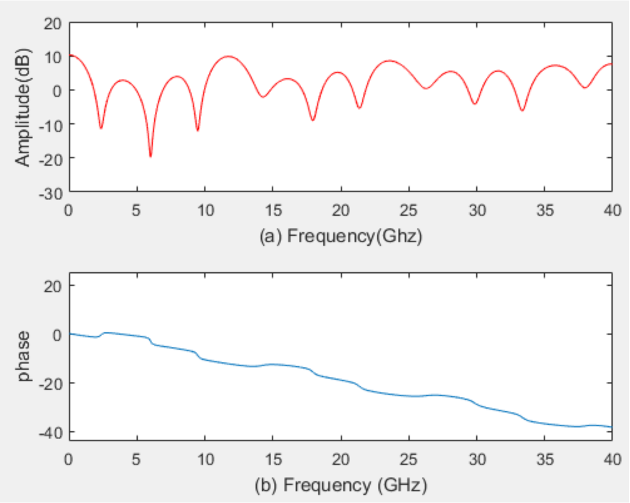

Fig. 4. Complete frequency response of the nonuniformly spaced microwave photonic filter when multiple optical sensors are involved.

In our simulations, we assume the total dispersion after the optical combiner is 34 ps/nm and the above optical sensors are measuring the following parameter changes: the refractive index change is 0.01, the change of twist angle is 5°, the lateral pressure changes by 0.01MPa, the temperature change is 20℃ , and the transversal loading equals to 1 gram.

As both the amplitudes and time delays of the five-tap microwave photonic filter have been changed, the filter becomes nonuniformly spaced. The complete frequency response of the resultant microwave photonic filter is shown in Fig. 4. It can be seen that the amplitude response is not periodic and the phase response is not linear as expected.

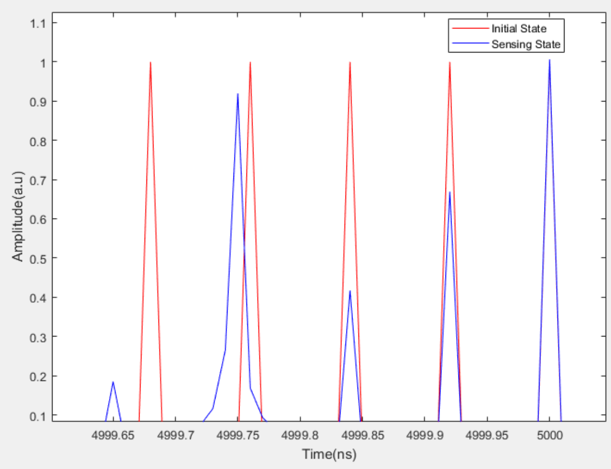

Fig. 5. Temporal impulse response of the nonuniformly spaced microwave photonic filter. Red: the initial response after calibration; blue: updated response representing the optical sensor information.

The temporal impulse response of the filter can be obtained via inverse Fourier transform of the frequency response with the results shown in Fig. 5. The initial response of five uniformly spaced taps is also shown in red for comparison. It is obvious that the response of reference arm remain unchanged. By comparing the change of amplitude and time delay for each tap, all the optical sensors can be interrogated simultaneously.

For example, for the first FP-based refractive index sensor, the amplitude is reduced to 0.68, which matches well with the expected value of 0.66. The second TFG-based twist sensor shows reduced amplitude of 0.4, which is in good agreement with the 5-degree twist angle. The third FBG-based pressure sensor presents a time delay shift of 12.2 ps, matching the applied pressure of 0.36 MPa. The slight variation in amplitude is due to the limited temporal resolution of the inverse Fourier transform. The forth sensor tap indicates both amplitude change of 0.19 and time delay shift of 17.7 ps, which match the given temperature change and loading added.

IV. CONCLUSION

Most exiting microwave photonic delay-line filter based optical sensor interrogation methods are based on linear phase frequency response, hence only supporting interrogation a small number of optical sensors with limited types. In this work, we propose to use a nonuniformly spaced microwave photonic delay-line filter for optical sensor network interrogation. As both amplitude and phase response of the filter are considered, multiple optical sensors with different types are interrogated simultaneously. This new design provides a promising candidate in microwave photonics enabled high-resolution and large-scale optical sensor network interrogation.

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