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 photonics 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.

\[ H(\Omega) = \sum_{k=0}^{N-1} a_k e^{-j\Omega \tau_k} \]  

where \( \Omega \) is the angular microwave frequency, \( N \) is the total number of filter taps, \( a_k \) and \( \tau_k \) 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.

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.
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 equals to 1 gram. 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.

REFERENCES


