Review

Microwave Photonic Signal Processing and Sensing Based on Optical Filtering

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Abstract: Microwave photonics, based on optical filtering techniques, are attractive for wideband signal processing and high-performance sensing applications, since it brings significant benefits to the fields by overcoming inherent limitations in electronic approaches and by providing immunity to electromagnetic interference. Recent developments in optical filtering based microwave photonics techniques are presented in this paper. We present single sideband modulation schemes to eliminate dispersion induced power fading in microwave optical links and to provide high-resolution spectral characterization functions, single passband microwave photonic filters to address the challenges of eliminating the spectral periodicity in microwave photonic signal processors, and review the approaches for high-performance sensing through implementing microwave photonics filters or optoelectronic oscillators to enhance measurement resolution.

Keywords: Microwave photonics; photonic signal processing; photonic filtering; single sideband modulation; single passband microwave photonic filter; optical sensors

1. Introduction

The low-loss and large available time-bandwidth product capability of fiber optic systems makes them attractive, not only for transmission of signals, but also for processing of high-speed signals [1–6]. The inter-disciplinary field of microwave photonics, which combines microwave engineering and optoelectronics, has rapidly expanded due to the microwave photonics offers, including immunity to electromagnetic interference, the ability to realize true-time delay lines [7,8], the ability to tune the filter center frequency over a wide range with shape invariance [9], the ability to control both phase and amplitude independently [10], and a fully programmable capability [11,12]. The ability to tackle wideband fibre-fed distributed antenna signal processing allows microwave photonics to have diverse applications primarily targeting areas in defense, fiber-radio, and radio astronomy.

Optical filters are an enabling technology for photonic systems with the most obvious application being to demultiplex very closely spaced channels, and they also play a major role in gain equalization and dispersion compensation [13]. They are one of the most essential and fundamental building blocks for various signal-processing operations. Work in this field has attracted a great deal of attention, with recent trends being directed towards photonic integration, as reported by several groups spanning platforms such as silicon photonics [1,14,15], silicon nitride [16], and III–V semiconductors [17].

In this paper, we present recent new optical filtering techniques for wideband signal processing via microwave photonics including optical single sideband modulation and spectral characterization, single passband microwave photonic filters exhibiting narrowband radio frequency (RF) response and shape-invariant tuning, and microwave photonics for sensing applications. This paper is organized as follows. Section 2 describes integrated optic approaches for optical single sideband (OSSB)

modulation. Section 3 presents single passband microwave photonic filters, which can suppress the harmonic passbands. Finally, Section 4 describes microwave photonic for sensing with extremely high-resolution performance.

2. Optical Filtering for Single Sideband Modulation and Spectral Characterization

RF-over-fiber (RoF) is an effective technique for wireless-optical systems including 5G, because it provides advantages including simpler antenna remote units (as no frequency conversion is required), centralized frequency channel management, and central office (CO) equipment sharing, as well as the capability to readily support multiple wideband signals [5,18]. However, an important disadvantage is dispersion-induced fading within the fiber, which becomes more of a problem as the RF spectrum is pushed to higher frequencies. This limitation can be overcome by using OSSB modulators. The OSSB scheme is also widely used in microwave photonic controlled phased array antennas and phase shifters [19,20], and in the optical vector network analyzer systems because it enables the important feature of direct mapping between the optical and electrical domains while also suppressing the dispersion-induced power penalty [21–23].

Various approaches have been reported for generating OSSB modulation. The conventional technique [24] and its extensions [25] comprise the use of an electrical hybrid coupler to obtain orthogonal RF signals that are applied to the optical modulator. This approach suffers from a limited modulated bandwidth, principally because of the use of the electrical hybrid coupler. All-optical approaches to realize OSSB have been presented, based on optical filters to eliminate one of the optical sidebands in an intensity modulation or phase modulation scheme [18,26]. This has been demonstrated by different approaches such as phase-shift fiber Bragg gratings [27] or stimulated Brillouin scattering (SBS) [28], or whispering gallery mode resonators, which are limited to either fixed frequency operation or narrowband operation [29].

A particularly attractive approach is to use optical microring resonator structures because they are integrated and hence they are small and exhibit excellent performance [30,31]. OSSB has been achieved via the use of a ring resonator assisted Mach–Zehnder interferometer to suppress the optical sideband for RF signals between 1.2 GHz and 2.2 GHz [32]. In Reference [33], the use of a parallel dual-ring modulator and a quadrature hybrid coupler enabled the operation at 30 GHz. In addition to dispersion penalty elimination in optical fibre microwave transmission, OSSB with large sideband suppression across wide RF frequencies also presents new applications to optical vector network analyzer for measuring the spectral response of both the amplitude and phase of optical components.

An OSSB with a sideband suppression of 23 dB has been achieved via an optical bandpass filter based on high order coupled-resonator optical waveguides (CROW) [34], which reduces RF power ripple to around +1 dB for wideband transmission of RF signals in a dispersive medium with a group delay slope of 330 ps/nm. When using the OSSB modulator in an optical vector network analyzer application, it can be noted that as the order of the microring CROW filter increases, the sideband suppression ratio is also increased, thus causing an obvious reduction in both the magnitude and the phase measurement errors. For a 6th-order CROW filter used for measuring the optical notch filter as a testing example, the simulated maximum magnitude deviation and the phase deviation are less than 0.4 dB and 2°, respectively [35]. In the experiment, 3200 effective points over a span of 20 GHz have been obtained, thus resulting in a measurement resolution of 6 MHz. It can be noted that the resolution can be easily improved to kHz by increasing the measurement points and altering the RF sweep range, without the need for adjusting of the rest of the setup.

In Reference [36], the use of the weak EIT-like design has enabled enhancement of the bandwidth of an integrated silicon-on-insulator (SOI) filter while maintaining a high rejection ratio and high slope steepness, thus increasing the range of operating frequencies possible for the generation of OSSB modulation. Figure 1a shows experiment setup that was performed to verify the principle of the weak EIT-like notch micro-ring filter for optical sideband suppression. This has achieved better than 29 dB of optical sideband suppression ratio for high frequency signals (17–35 GHz), as shown by

the experimental results in Figure 1b–d, while realizing electrical power ripple reduction to less than ±1.25 dB for RF frequency up to 30 GHz. It has also been used to demonstrate the high-resolution performance of an optical vector network analyser, by measuring the SBS filter amplitude and phase response, and by performing wide-band measurements over 10–30 GHz of an on-chip SOI-based micro-ring resonator.
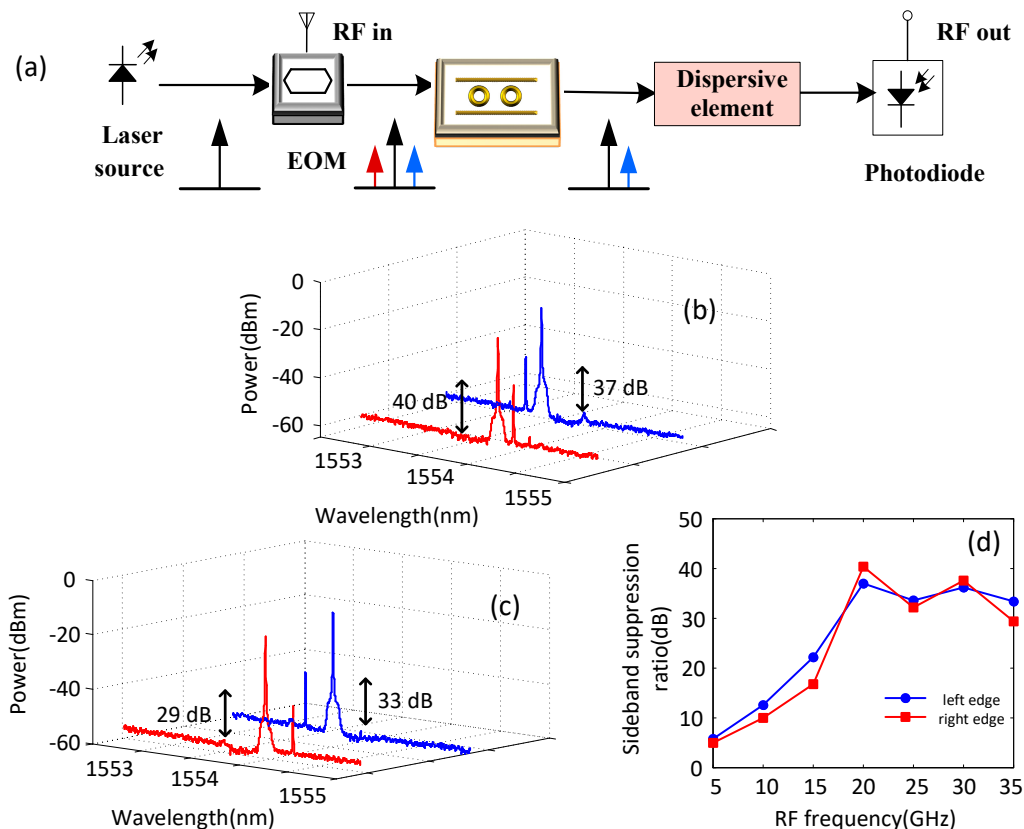
Figure 1. (**a**) Schematic of the experimental setup of the OSSB modulation system, (**b**) experimental results of the measured OSSB at 20 GHz, (**c**) experimental results of the measured OSSB at 35 GHz (where the blue line represents the upper sideband suppression of the left edge while the red line represents the lower sideband suppression of the right edge of the fabricated dual-ring weak EIT-like notch filter), and (**d**) the sideband suppression ratio as a function of frequency from 5–35 GHz.

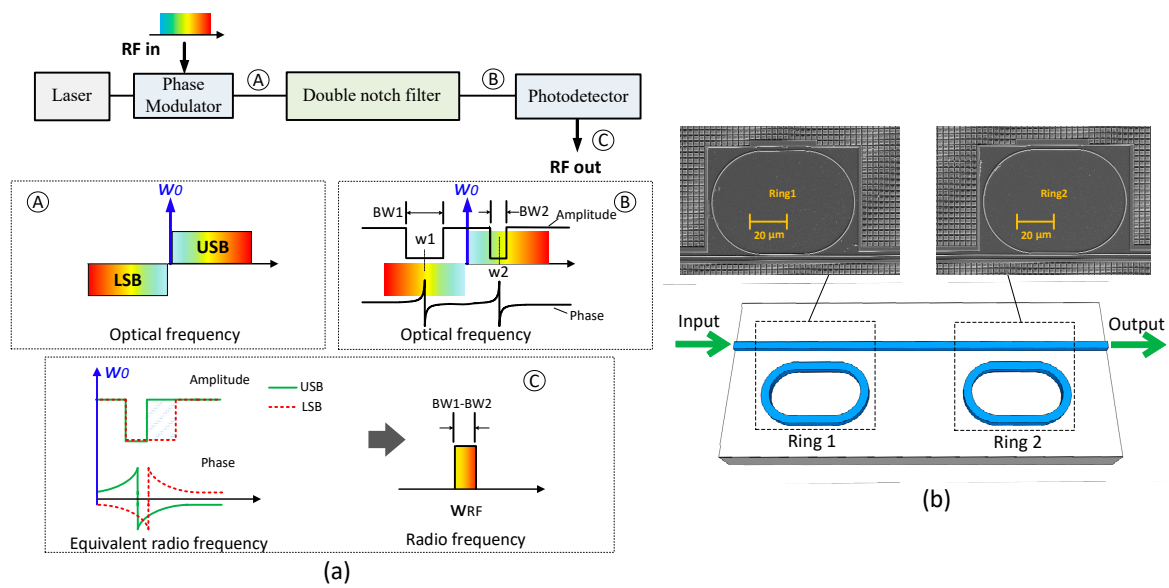## 3. Optical Filtering for Single Passband Microwave Photonic Filter

Microwave photonic filters provide advantages of extremely wide tunability, reconfigurability and electromagnetic immunity [37]. Conventional microwave photonic filters are based on finite impulse response (FIR) structures consists of multi-taps optical signals where they are weighted, delayed, and summed before the photodetection [37–44]. While the FIR structure has inherent flexibility in realizing arbitrary transfer function, it presents undesired spectral periodicity of multiple harmonic passbands with a period given by the free spectral range [1–3]. Therefore, for wideband and continuously tunable applications, it is particularly important to realize microwave photonic filters that have a single passband to avoid the crosstalk and spectral overlapping from undesired RF passbands within the spectral range of interest.

To solve this problem, optical filtering techniques have been implemented to produce single passband microwave photonic filters and can be broadly divided into two principal categories. The first one builds upon the spectrum slicing techniques to provide a cost-effective solution for achieving high-resolution signal processing [45–47]. In [47], single passband microwave photonic filter structure was achieved by controlling the dispersion-induced RF fading and the carrier suppression effect,

so that the notch frequencies fall on the periodic spectral resonances. The development in single passband spectrum-sliced microwave photonic filter are either based on the Fourier-transform of optical spectrum into RF domain [11,48–50], or the shifted dispersion-induced RF fading using a dual-input Mach-Zehnder interferometer configuration [9,51–53]. Optical filtering techniques have also been extensively applied to apodize broadband optical source with a Gaussian windowing function, hence greatly increasing the filter sidelobe suppression ratio [9,51–53]. A shape-invariant single passband microwave photonic filter with an improved sidelobe suppression to nearly 30 dB has been demonstrated in Reference [9] by implementing the Gaussian optical spectrum.

The second category is based on utilising optical filters to manipulate the RF sidebands of the modulation schemes and to realise single passband microwave photonic signal processors through direct mapping from the optical domain to the electrical domain [54–69]. This technique features a simple configuration to achieve an extremely wide frequency tuning range. The majority of the techniques are based on the phase modulation scheme due to the absence of bias drift problems. The concept of using stimulated Brillouin scattering (SBS) based filtering of optical signals to realise narrowband RF selectivity is an attractive approach for implementing high-resolution single passband filters, and this operates by breaking the RF phase modulation sideband symmetry using the SBS gain and loss spectrum [54–61]. An RF filter with a bandwidth of about 20.6 MHz, less than $\pm$1.2 dB of amplitude fluctuation and over 30 dB of out-of-band rejection ratio within the whole tuning range of 20 GHz has been obtained by using optical fiber as the gain medium [56]. Optical and microwave photonic filtering techniques based on the SBS effect have subsequently been presented using miniaturization by means of photonic integrated waveguides. A chalcogenide spiral waveguide with a total length of 11.7 cm has been utilized to obtain a microwave photonic filter with a continuous tuning range of 30 GHz without RF passband degradation [61].

The phase-modulation to intensity-modulation conversion approach [62–69] is effective and can work well to achieve a single passband RF response, provided the optical notch filter does not introduce additional phase outside its notch region. Unfortunately, this is not usually the case, and in practice the extra non-zero phase introduced by the optical filter outside its notch bandwidth prevents full cancellation of the anti-phase modulation sidebands, with the consequent result that the extinction ratio of the RF filter and its shape factor are significantly degraded. To address the phase issue, use of an additional liquid-crystal-on-silicon device has been presented to achieve an out-of-band rejection ratio of above 20 dB [68]. However, this approach has limitations for integration. An integrated-based technique employing a cascaded pair of microring resonators on SOI platform has been presented to achieve a tunable single passband microwave photonic filter with improved shape factor and extinction ratio [69]. It is based on two optical notch filters that have slightly different stopbands and phase shifts, and are located on each side of the optical carrier. The structure could compensate the inherent phase of the optical filter and achieve a tunable bandwidth of the single passband in the RF filter by controlling the relative offset between the two optical filter bandwidths. Figure 2a shows the topology of the single passband microwave photonic filter, which enables wideband tunability and adjustable bandwidth. The key building block comprised a cascaded pair of all-pass ring resonators, where one was implemented with a resonance splitting effect and one was without the effect, each of which consisted of a straight bus waveguide and racetrack waveguides have a dimension of 220 nm by 450 nm as displayed in Figure 2b. The novel concept demonstrated a significantly reduced single passband bandwidth and shape factor with an improved out-of-band suppression ratio of around 20 dB, as well as a wide and shape invariant filter single passband that is continuously tunable from 6 GHz to 17 GHz, as shown in Figure 3.

Figure 2. Schematics and illustration of the (**a**) single passband microwave photonic based on optical double notch filter, and (**b**) the optical double notch filter.
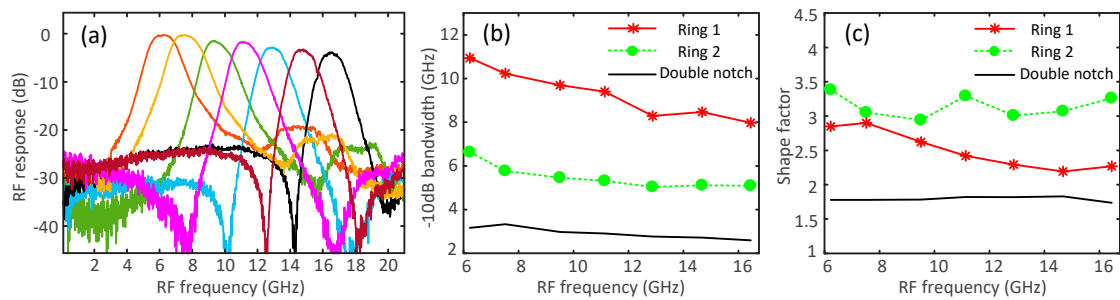
Figure 3. (**a**) Measured RF responses, (**b**) −10-dB bandwidths, and (**c**) shape factors at −10-dB/−3-dB bandwidth for single passband microwave photonic filter based on single and double notch filters.

## 4. Microwave Photonic Sensing Based on Optical Filtering

A need exists for sensors that have extremely high resolution, or which need to operate with immunity to electromagnetic interference, as well as exhibiting inertness in chemical and biological applications, compactness, light-weight, and ability to operate in harsh environments. Photonic sensors can fulfil these requirements. Techniques based on microwave photonics, in which the wavelength shift of the optical sensor is converted directly into the variation of an RF frequency signal are particularly attractive [70,71]. The hybrid approach of using microwave photonics as an extension to conventional optical sensors has demonstrated significant merits in enhancing the sensing speed, sensitivity, and resolution, where a minute optical changes determined by the sensing information can be converted into a large variation in the RF domain [70–73].

The use of FIR microwave photonic filters with discrete multi-taps for optical sensing method translates the targeted measurand information on optical delays between different taps of the filter into RF frequency variation of the microwave photonic filters [74,75]. For example, a two-tap incoherent notch microwave photonic filter based transverse load sensor has been implemented to determine wavelength separation changes of the fiber Bragg gratings by detecting the notch resonance frequency shifts of the RF filter response [75]. Another technique to implement the interrogation of optical sensors is via an optoelectronic oscillator (OEO) whose microwave oscillation frequency is determined by the resonant wavelength of the optical device that is employed for sensing. In the OEO based sensing topology, the resonance of the optical filtering device based on the measurand information determines

the generated microwave oscillation frequency [71]. The OEO offers a high-speed and high-resolution sensing solution by translating the optical domain resonance wavelength change caused by a strain, temperature, refractive index or transverse load to a frequency change of an RF electrical spectrum [72]. Various OEO based sensing architectures have been reported [76–82], which includes using phase-shifted fiber Bragg grating (PS-FBG) as strain sensors [76], polarization-maintaining PS-FBG for temperature-insensitive transverse load sensing [77,78], temperature sensors using a single laser source [79], or a Mach-Zehnder interferometer structure built by a broadband optical light source [80], where the frequency drifting problem of the single laser source was eliminated [81]. Looking to the future, the development of a compact and portable OEO sensor in a miniaturized platform has attracted significant interest. An integrated photonic sensor based on an OEO with an on-chip sensing probe that is capable of realizing highly sensitive and high resolution optical sensing has been presented [82]. The integrated SOI single ring resonator exhibits an optical notch filtering response and implements a RF single bandpass filter in an OEO system configuration. The side modes of the OEO were effectively suppressed by more than 30 dB, leaving a dominant peak RF signal at the oscillating frequency, and due to the high thermal coefficient of the SOI based microring resonator and the oscillator configuration. Thus, a small temperature change generated on the microring resonator sensor will be reflected by a large RF frequency shift in the OEO output that can be measured with very high temperature resolution of 0.02 °C.

Direct optical-domain to RF-domain mapping by manipulating the two sidebands of an optical carrier provides a potential effective realization of a microwave resonant based optical sensing system [83,84]. Conventional approaches operate by converting a change in the measurand into (i) an optical wavelength shift in the resonance spectrum, which is then interrogated by an optical spectrum analyzer (OSA) [85,86], or (ii) into an intensity variation [87]. Both these approaches are limited by the interrogation speed and resolution, especially when using microring resonators where degradation in the quality (Q) factor due to fabrication errors arising from processing uncertainties is inevitable. Alternative hybrid approaches using OEO based sensors by means of a SOI based single all-pass microring resonator [82] are also largely dependent on the bandwidth of the optical filter due to the mode selectivity, which means a high-Q microring resonator is still essential and critical in the system. To address these issues, we recently reported a novel microwave photonic sensing interrogation technique to provide high notch rejection with narrow width throughout the entire sensing range in combination with a reflective SOI based microring resonator based optical notch filter as a sensing probe, as displayed in Figure 4 [88]. By adjusting the rejection depth of the optical broadband notch enhancement filter, the two sidebands can be made equal in amplitude, while they have an anti-phase relationship, thus an ultra-high rejection is achieved after detecting the photocurrent, thus removing the need for a high-Q microring optical notch filter. Since the microring is essentially a point sensor, it also enables the capability to perform remote measurements at locations with limited accessibility. This system adopts a simple configuration, requiring only a fixed laser diode, a conventional phase modulator (PM), a wideband optical notch equalization filter, a reflective single microring as a sensing window, and a photodiode (PD) to convert and enlarge the temperature changes in the microwave photonic/RF domain. The complexity and cost of the system can be further reduced by implementing the broadband optical equalisation filter by means of a fixed optical notch filter in practical applications. A temperature sensor has been demonstrated experimentally as a proof-of-concept. When ambient temperature was varied between 23.69 °C to 25.37 °C, an ultra-high notch rejection of the microwave photonic filter of about 60 dB has been achieved over a large RF range, as depicted in Figure 4b. A small, temperature-dependent shift in the optical resonant frequency leads to a large change in the RF notch frequency location that produces a high sensitivity of 11.57 GHz/°C, as illustrated in Figure 4c. It demonstrates the ability to convert a 0.03 °C small temperature change, which is limited by the equipment resolution of the temperature controller, to a significant frequency shift as large as 324 MHz, whereas by comparison if conventional optical spectrum interrogator techniques were used such that a minor temperature change would

not be detectable. This demonstrated a sensing probe system that is robust, easy to be operated, and creates more flexibility for various point measurements with significantly improved sensitivity, which is highly attractive for applications that require accurate detection.
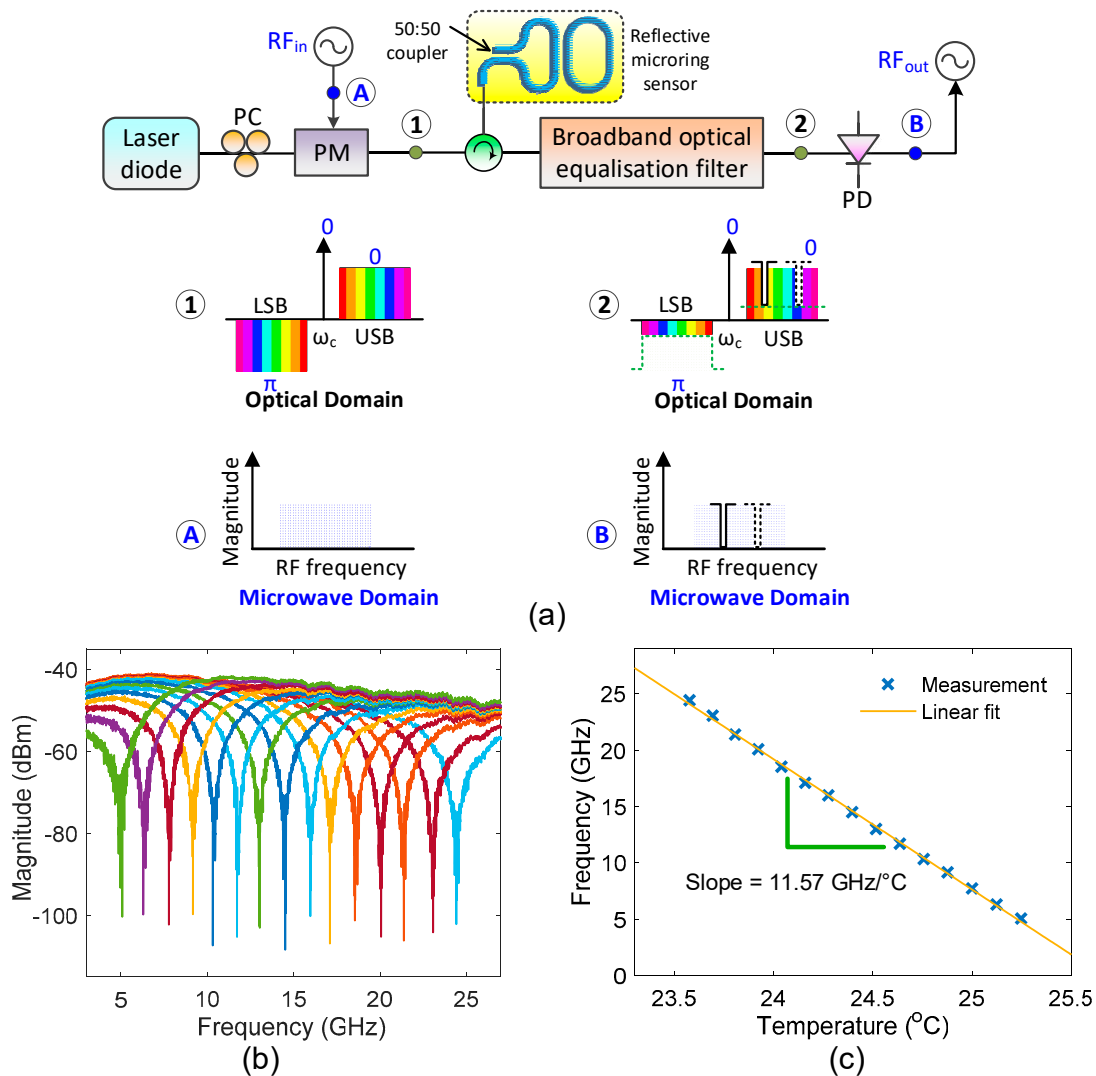
Figure 4. Schematic diagram and measurement results. (**a**) Schematic diagram and operational principle of the sensing scheme. (**b**) Measured RF response of the high sensitive temperature sensor. (**c**) Measured narrowband notch location changes of the microwave photonic filter corresponding to the applied temperature variations.

5. Conclusions

Microwave photonics based on the use of optical filtering techniques offer the intrinsic advantages of electromagnetic immunity, wideband operation bandwidth, high-resolution for both signal processing and sensing applications. Recent progress in microwave photonics based optical filtering approaches has been described with reference to optical single sideband modulation schemes, single passband RF signal processors and microwave photonic sensing structures. Particular attention has been focused on describing the novel techniques reported to overcome the major limitations of conventional systems. These techniques will provide new capabilities to pave the development roadmap towards the evolution of high-performance optical filtering assisted microwave photonic signal processing and sensing.

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