Microwave Photonic Self-Adaptive Bandpass Filter and its Application to a Frequency Set-on Oscillator

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Abstract — Linear frequency networks are a class of analog systems comprising nonlinear elements but which have a linear relationship between the input and output instantaneous frequency. Examples of such networks find applications in self-adaptive bandpass filters and frequency set-on oscillators. Early implementations of these linear frequency networks were built exclusively with RF and microwave components, resulting in limited bandwidths. Here, we demonstrate their implementation with microwave photonics, which enables broader bandwidth operation with lower propagation losses (and hence longer delay lengths) for the development of, for example, high-Q set-on oscillators.

Keywords — microwave photonics, oscillators, microwave photonic filters, instantaneous frequency, linear frequency network.

I. INTRODUCTION

Over the past few years, there has been a significant interest (especially in electronic warfare systems that operate over multi-octave bandwidths with frequency hopping) in the use of photonics to process the instantaneous frequency (IF) [1]. Adaptive electronic filters have also attracted much interest for this application. An adaptive filter can control its response to maximise the signal-to-noise ratio (SNR), for example, in a communication channel [2]. Additionally, an electronic set-on oscillator, which is a loop oscillator formed by applying feedback to an adaptive filter would be an ideal device for electronic warfare applications in conjunction with a baseband sampling and digital storage system [3]. Such self-adaptive bandpass filters and frequency set-on oscillators belong to a class of analog systems termed "linear frequency networks" [3]. The central theme in linear frequency networks is the use of band-limited nonlinear components such as upper/lower-sideband mixers, frequency multipliers and frequency dividers, that are configured such that there is a linear relationship between the input and output instantaneous frequencies, thus allowing definition of a linear transfer function for the instantaneous frequency. However, operation over several octaves of bandwidth is difficult with conventional microwave components due to their band-limited nature. Thus, microwave photonics (MWP) technology is an ideal option to overcome the bandwidth limitation of electronic IF systems so as to operate beyond 60 GHz.

Microwave photonic systems employ optoelectronic, optical and microwave components in order to generate, distribute and process microwave signals [4]. Key advantages include a large time-bandwidth product, low optical attenuation, and immunity to electromagnetic interference. Consequently, MWP technology has been used to realize reconfigurable filters and low phase noise oscillators, with the latter being enabled by the relatively long optical delays required for high-Q operation. Microwave photonics has been applied recently to linear frequency networks [5], illustrating a specific example of a MWP self-adaptive bandpass filter, which is capable of forming a bandpass characteristic around a rapidly varying carrier frequency.

In this work, we will present three applications of microwave photonic frequency linear networks, viz.: a microwave photonic self-adaptive filter (SAF), an optoelectronic oscillator (OEO) based on a self-adaptive filter and a set-on microwave photonic oscillator.

II. MICROWAVE PHOTONIC SELF-ADAPTIVE BANDPASS FILTER

According to [3], self-adaptive bandpass filters are devices which produce bandpass filter characteristics around a signal carrier frequency. This concept was recently extended to microwave photonic linear frequency networks [5]. A microwave photonic self-adaptive bandpass filter (MWP-SABPF) is a photonic implementation of the corresponding microwave self-adaptive filter in [2], bringing a series of advantages (e.g. tunability, reconfigurability, and electromagnetic immunity).

The magnitude of the linear frequency transfer function of the overall MWP-SABPF is [3]:

\[
\left| \frac{\Omega_2}{\Omega_1} \right|_{s=j\omega} = \cos^2 \left( \frac{\tilde{\omega} \tau}{2} \right)
\]

(1)

where \( \Omega_1 \) and \( \Omega_2 \) are the Laplace transforms of the instantaneous frequency of the signal at the input and output respectively, where \( \tau \) is due to the delay line element. Equation (1) exhibits a quasi-lowpass characteristic in the pseudo-frequency domain \( \tilde{\omega} \) where it is noted that the variable, \( \tilde{\omega} \), is not the frequency of the RF signal, but in essence relates to the spectrum of the instantaneous frequency. Due to the periodic nature of such a transfer function, a true low-pass characteristic cannot be obtained, but aliasing errors may be removed due to band-filtering [2].

A. Experimental Procedure and Results

The experimental set-up (Fig. 1) is realized with a 1550.12 nm DFB laser of 2 MHz-linewidth, subsequently connected to
a Mach-Zehnder modulator with a $V_x$ of 4.9 V (MZM-1). A single-mode fiber of length $L$, interconnects MZM-1 with a second Mach-Zehnder modulator (MZM-2, with identical $V_x$ of 4.9 V). The RF electrodes of both MZMs are driven with the frequency divider output via a 3-dB RF coupler, which accepts the input signal to be filtered. Finally, a high-speed photodiode (PD) with an electrical bandwidth of 60 GHz, detects the frequency discriminated microwave signals which are amplified by a broadband microwave amplifier of gain and noise figure of 26 dB and 6 dB respectively.

![Fig. 1. Microwave photonic self-adaptive bandpass filter. DFB: Distributed feedback laser, MZM: Mach-Zehnder modulator, PD: Photodiode, MA: Microwave amplifier, FD: Frequency divider, PS: (Microwave) power splitter.](image)

The measured output spectrum of the filtered signal is illustrated in Figs 2a and 2b. The output microwave spectrum was measured for fiber lengths of 100 m and 1 km, which correspond to a frequency spacing of 1 MHz and 200 kHz respectively as presented in Fig. 2a, using a single microwave generator of 10 dBm at 1 GHz that was phase modulated with an internal noise source. The $\cos^2$ filtering profile acts on the modulated noise, suppressing the rapidly varying terms of the instantaneous frequency.

The phase noise modulated input signal prior to filtering as compared to the output spectrum is shown in Fig. 2b, for a delay line of 1 km. The output signal contains additional noise components due to the noise added from the wideband microwave and optical amplifiers that are used to compensate the optoelectronic conversion losses.

![Fig. 2. Measured spectrum (centered at 1 GHz) of: (a) the MWP-SABPF output for a noise-modulated 1 GHz input signal. The periodicity of the ripples is determined by the length of the fiber delay. SPAN: 5 MHz and RBW: 1 kHz,(b) the signal before and after filtering. SPAN: 30 MHz and RBW: 1 kHz.](image)

**B. Transfer Function measurement**

The transfer function of the MWP-SABPF, relating the output instantaneous frequency to the input instantaneous frequency cannot be measured using a vector network analyser (VNA) since the filter would simply track the swept frequency of the VNA. Thus, we employed a two-tone test method [2], in which two RF frequency synthesizers at frequencies $f_0$ and $f_0 + \Delta f$, with power levels of 0 dBm and -10 dBm respectively were used at the input section of the MWP-SABPF. A center frequency of 2 GHz was chosen for $f_0$, while the frequency offset $\Delta f$ for the second source was varied from 22.28 MHz to 23.5 MHz. At the output section of the MWP-SABPF, the power gain variations of the detuned tone were tracked as a function of the frequency offset $f_0 + \Delta f$ (Fig. 3). Consequently, the power gain difference (in dB) represents the second tone power variation across the detuning spectrum with respect to the input signal power at the frequency $f_0 + \Delta f$ of the same tone. The measured data resemble a $\cos^2$ profile, defined by Equation (1) confirming the frequency carrier tracking ability of the MWP-SABPF. The filter locks to the 0 dBm tone (first tone) at $f_0$ of 1 GHz, while the -10 dBm tone (second tone) at the frequency $f_0 + \Delta f$ experiences an attenuation with a period of 2 MHz that corresponds to the delay (500 ns) or the frequency spectral range of the 100 m of standard single mode fiber used as the delay element $L$ in Fig. 1. The extinction ratio for the measured transfer function is 20 dB while for the theoretical model it is 37 dB. This discrepancy is due to the losses of the MWP system which were not included in the theoretical model.

The transfer function measurements were acquired with a tone separation larger than 20 MHz in order to avoid spectrum overlapping and synchronization between the two frequency synthesizers.

**III. OPTOELECTRONIC OSCILLATOR BASED ON SELF-ADAPTIVE FILTER**

**A. Experimental Setup and Results**

With reference to Fig. 4, a quadrature biased Mach-Zehnder modulator (MZM-1) with a $V_x = 4.9$ modulates the output of a distributed feedback laser (DFB) emitting at
a wavelength of $\lambda = 1550.12$ nm with a 2 MHz linewidth, -140 dB/Hz relative intensity noise (RIN) and 11-dBm power which is subsequently connected to a fiber delay line of $L=100$ m and a second Mach-Zehnder modulator (MZM-2) with a $V_n = 4.9$. An erbium-doped fibre amplifier (EDFA) compensates the insertion losses (8-dB) of both MZMs. The optical signals are converted to the electrical domain by a high-speed photodiode (PD) of 60 GHz RF bandwidth. The generated RF output signal is then passed to a wideband low noise microwave amplifier (LNA). The frequency divider (FD) divides the RF frequency up-converted from the series MZMs; due to the multiple spurious tones generated from the non-lineairties of the FD, a narrowband microwave filter centered at 10 GHz with a bandwidth of 70 MHz is subsequently connected. An additional LNA is placed in the loop in order to increase the loop-gain to above unity before being fed to both RF ports of MZM-1 and MZM-2 through a power splitter, thus closing the complete OEO loop.

The SAF-OEO requires sufficient open-loop gain and optical power in order to sustain oscillations. After meeting these conditions a free running oscillation is observed. The open-loop response of the SAF-OEO is illustrated in Fig. 5. The VNA is used to measure the frequency response of the SAF-OEO, indicating that a gain of 20 dB is required to force the optoelectronic feedback loop to oscillate. The free spectral range (FSR) between the modes is equal to 2 MHz, with this mostly determined by the delay of the optical cavity, while the oscillation frequency is determined by the dominant mode inside the microwave filter passband.

The measured electrical spectrum of the proposed OEO based on a self-adaptive filter is compared to a conventional single-loop OEO in Fig. 6. The center frequency of both oscillating signals is roughly 10 GHz; this value is determined by the microwave bandpass filter. The SNR of the single-loop SAF-OEO is degraded by 12 dB compared to the conventional OEO. The SNR of the SAF-OEO can be improved by optimizing the mixing section (cascaded MZMs) of the loop, e.g. using a dual parallel MZM to overcome the losses and using more optical gain in the loop, thus avoiding an excessive number of microwave amplifiers.

However, the SAF enclosed in the cavity of the OEO, is seen to improve the spurious suppression - the side-modes generated from the cavity element. Comparing the side-mode suppression ratio (SMSR) of the single-loop OEO (55 dB) with the SAF-OEO (62 dB) there is 7 dB improvement. The SMSR value can be further enhanced by increasing the SNR of the SAF-OEO.

**IV. MICROWAVE PHOTONIC SET-ON OSCILLATOR**

A microwave photonic set-on oscillator (MWP-SO) is obtained when the feedback optoelectronic loop is closed and an instruction pulse is applied to the loop as illustrated in Fig. 7. After many recirculations of the signal within the loop, stable oscillations at the mode closest to the injected instruction pulse frequency are observed. Such adaptive oscillators are useful in many different scenarios where stable selection and generation of microwave tones are required.

**A. Experimental Setup and Results**

The proposed microwave photonic set-on oscillator was implemented as illustrated in Fig. 7, using a 1550.12-nm DFB laser, directly connected to a Mach-Zehnder modulator.
with a $V_\pi$ of 4.9 V (MZM-1). A single-mode fiber with length $L$, interconnects MZM-1, with a second Mach-Zehnder modulator (MZM-2) with a $V_\pi$ of 5.1 V. Next, an EDFA is placed in the loop to compensate the insertion losses from the MZMs. The lightwave signals are then converted to electrical form through a high-speed photodiode. The resulting RF signal is then amplified with its frequency being divided by two. The electrical bandpass filter (EBPF) cancels the spurious signals generated from the nonlinearities of the frequency divider, and the frequency divided signal is then amplified and synchronized with an instruction pulse from a frequency synthesizer added to the optoelectronic loop. The pulse length is almost equal to the delay which results mainly from the fiber spool (500 ns) and the microwave components.

The measured spectrum in Fig. 8 displays the individual spectral lines created by the pulse generator; the line spacing is equal to the pulse period (pulse repetition interval) of 20 μs. The measured output spectrum of the oscillating signal for the MWP-SO is depicted in Fig. 8, indicating the stable mode oscillations. It was observed that the MWP-SO jumped into the optoelectronic loop mode closest to the instruction frequency of the pulse generator. The modulation pulse length for the instruction frequency required to trigger the oscillator is found to be approximately equal to or slightly less than the delay in the optoelectronic feedback loop [6].

![Fig. 7. Experimental setup of the microwave photonic set-on oscillator. DFB: Distributed feedback laser, MZM: Mach-Zehnder modulator, PD: Photodiode, MA: Microwave amplifier, FD: Frequency divider, PS: (Microwave) power splitter.](image)

![Fig. 8. Several modal oscillations set-up in the MWP-SO. Center frequency: 10 GHz, SPAN: 5 MHz, RBW: 1 kHz.](image)

**V. CONCLUSION**

We have proposed and experimentally demonstrated three microwave photonic implementations of linear frequency networks: (a) A self-adaptive bandpass filter, exhibiting a quasi-lowpass transfer function for the instantaneous frequency of band-limited RF signals, that maps to the passband characteristics in the frequency spectrum. The MWP-SAF is able to track the carrier frequency and simultaneously remove the rapid phase variations; (b) An optoelectronic oscillator based on a self-adaptive bandpass filter, which has been experimentally demonstrated and exhibited a side-mode suppression improvement of 7 dB compared to the conventional single loop OEO. In the future, the dynamics and the phase noise of the OEO will be investigated in order to study the effects of the SAF inside the cavity of the OEO; (c) A microwave photonic set-on oscillator has been demonstrated, showing excellent mode stability at 10 GHz. The aforementioned systems have potential applications in modern electronic warfare systems (for frequency hopping coherently modulated signals), communications (optimizing the SNR) and where fast phase locking recovery is required.

**REFERENCES**


