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Invited Paper

Instantaneous microwave frequency measurement using four-wave mixing in a chalcogenide chip

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ABSTRACT

We present the first instantaneous frequency measurement (IFM) system using four-wave mixing (FWM) in a compact photonic chip. We exploit the high nonlinearity of chalcogenide to achieve efficient FWM in a short 23 mm As_2S_3 waveguide. This reduces the measurement latency by orders of magnitude, compared to fiber-based approaches. We demonstrate the tuning of the system response to maximize measurement bandwidth (40 GHz, limited by the equipment used), or accuracy (740 MHz rms error). Additionally, we modify the previous FWM-based IFM system structure to allow for ultra-fast reconfiguration of the bandwidth and resolution of the measurement. This has the potential to become the first IFM system capable of ultra-fast accurate frequency measurement, with no compromise of bandwidth.

1. Introduction

Instantaneous frequency measurement (IFM) systems are used in microwave receivers to provide a fast (nanosecond range) estimate of the frequency of a detected signal [1]. Typical applications include radar warning receivers, electronic intelligence systems, and signal intelligence systems. These applications would greatly benefit from the development of IFM systems capable of extremely high frequency (EHF) band operation, as can be realized by optical processing of microwave signals [2]. Indeed, there have been numerous proposals for implementing high-bandwidth microwave IFM systems using optical components [3–18].

The recent emergence of the field of integrated microwave photonics (IMWP) is particularly well suited to the implementation of IFM systems [19], due to the reduced latency that integrated systems have over bulky components. This is a key benefit for IFM systems, complemented by the additional advantages of integration; namely low cost, weight, and power consumption [20]. Previous integrated IFM demonstrations have all relied on ring resonators in Si_3N_4 [21], InP [22], and Si [23] technologies. While impressive, the measurement bandwidth for these devices was limited by the free spectral range of the rings.

One particular IFM approach with no inherent measurement bandwidth limitation relies on nonlinear optical mixing to generate an idler whose power is dependent on the frequency of the input radio frequency (RF) signal [3]. The key feature of this all-optical implementation is that the only electronics it requires is a low-cost DC photodetector. This elegant yet simple technique was subsequently extended to implement a remoted IFM receiver [4], to enable amplitude independent operation [5], and to enhance the measurement accuracy to within 0.016% over an extremely high 40 GHz measurement range [6]. The attractive characteristics of this method are however diminished by the microsecond measurement delay induced by the long lengths of fiber required to achieve efficient optical mixing.

Nonlinear optics has already proven to be a powerful tool in the field of IMWP [24,25]. In this work, we harness the strong nonlinearity of a chalcogenide As_2S_3 rib waveguide to demonstrate an ultra-low latency, wideband IFM system reliant on four-wave mixing (FWM). The large nonlinear parameter $\gamma \sim 10\ m^{-1}\,W^{-1}$ (500 times larger than that of highly nonlinear fiber [26–28]) of our dispersion engineered waveguide allows us to achieve efficient FWM over a short 23 mm length, greatly reducing the latency of the IFM system to sub-nanosecond timescales. We perform IFM over a 40 GHz measurement bandwidth, limited by the equipment used, which is a record for an on-chip device. Moreover, we alter the structure of the previous FWM-based IFM system [3] to enable

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ultra-fast reconfiguration of the measurement resolution, and demonstrate frequency estimation with low 0.74 GHz root mean squared (rms) error.

2. Principle of operation

The basic structure of the current FWM-based IFM system is shown in Fig. 1(a). Two lasers with frequencies ω_1 and ω_2 are sent to an electro-optic modulator (EOM) where they are modulated by an RF signal of unknown frequency Ω. The modulation scheme used is double sideband with carrier, meaning that the two laser spectra acquire sidebands with frequencies $\omega_1 \pm \Omega$ and $\omega_2 \pm \Omega$. The two optical signals are then demultiplexed using a coarse wavelength division multiplexer (CWDM), and propagate through different lengths of fiber where the signal carried by ω_2 undergoes a time delay Δt relative to the signal carried by ω_1. Next, the two channels are recombined and launched through a nonlinear medium, in this case a chalcogenide (ChG) rib waveguide, where they are mixed generating new frequencies (i.e. idlers). Finally, a bandpass filter (BPF) is used to select one of the idler fields, and the power of this field is measured using an optical power meter (i.e. DC photodetector).

The optical mixing in the nonlinear medium is enabled by FWM, a process whereby the medium response is proportional to the cube of the optical field [29]. For the current purpose, it is enough to know that FWM generates new frequency components at $2\omega_1 - \omega_2$, and $2\omega_1 - \omega_2 \pm \Omega$. It is by measuring the optical power of these three new components, known collectively as the idler field, that we can obtain an estimate for the unknown RF Ω.

With reference to Fig. 1(b) and assuming that both optical carriers are significantly stronger than the modulation sidebands, it is simple to show that there are two ways to generate the idler component at $2\omega_1 - \omega_2 + \Omega$: that resulting from the mixing of components $(+\omega_1, +\omega_1, -\omega_2 + \Omega)$ with 3 permutations, and that resulting from the mixing of components $(+\omega_1, +\omega_1 + \Omega, -\omega_2)$ with 6 permutations. Each permutation contributes equally to the idler generation process, so that the total idler field generated by each FWM process must be a sum of all the permutations. The net idler component at $2\omega_1 - \omega_2 + \Omega$ is therefore a coherent sum of two mixing products

$$E_{2\omega_1-\omega_2+\Omega}(t) \propto (6 + 3e^{-j\Omega\Delta t})e^{j(2\omega_1-\omega_2+\Omega)t}e^{j\omega_2\Delta t} + \text{c. c.} \tag{1}$$

where c.c. represents the complex conjugate terms. The average optical power for this particular idler component can then be shown to be

$$P_{2\omega_1-\omega_2+\Omega} \propto \cos(\Omega\Delta t). \tag{2}$$

Eq. (2) holds even in the event of phase fluctuations between the two channels, as they propagate along different paths after being demultiplexed by the CWDM. This is because both idler terms present in the coherent sum in Eq. (1) experience the same phase fluctuations so that, while the phase of the total idler field changes, its power remains constant.

Using a similar procedure for the remaining idler components, and neglecting dispersion effects, it is possible to express the total average power of the idler as

$$P_{\text{idler}} = A + B\cos(\Omega\Delta t) \tag{3}$$

for some constants A and B, with $A \geq B$. This expression shows that, once the IFM system has been characterized (i.e. A, B, and Δt are known), it is possible to calculate the unknown RF Ω simply by measuring the average power of the idler, which can be done using a low-cost DC photodetector.

The response of the IFM system is presented in Fig. 2. There are two parameters of interest in this plot. The first is the range of RFs for which there is a one-to-one, or unambiguous, correspondence with optical power. This range, which defines the effective operational bandwidth of the IFM system, is inversely proportional to Δt. The second parameter is how accurately the IFM system can distinguish between two different frequencies. This *resolution* is equal to the slope of the system response: it increases with idler power, and is proportional to Δt. Greater *measurement resolution* leads to lower error in the frequency measurement.

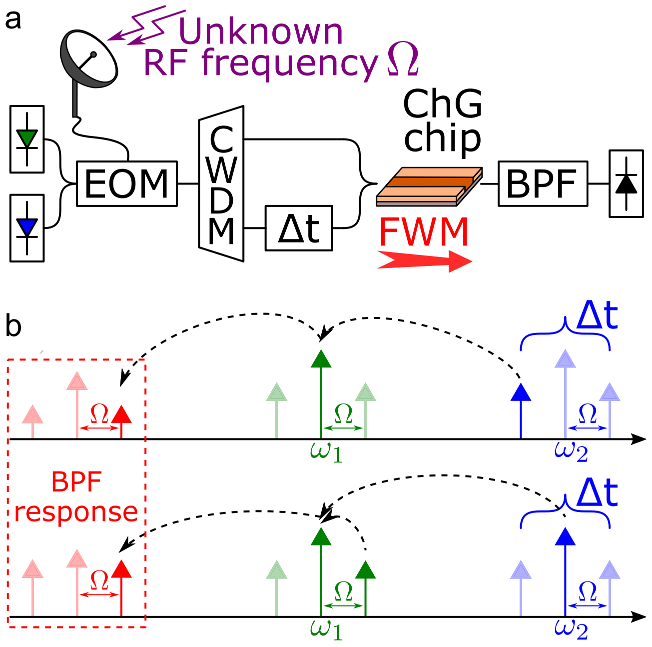

Fig. 1. (a) Structure and (b) operating principle for the FWM-based IFM system.

3. Experimental work

3.1. System characterization

The experimental setup used to implement the FWM-based IFM system is shown in Fig. 3. One semiconductor laser diode and one tunable laser were biased for continuous wave operation, *each* with 14 dBm output power, at wavelengths 1550.0 nm, and 1551.8 nm, respectively. The outputs from the two lasers were combined and sent through an EOSPACE 20 GHz Mach–Zehnder modulator (MZM), where they both underwent intensity modulation. The signal whose frequency would be measured was provided by an RF signal generator (SG), and fed to the modulator. The two optically modulated signals were then amplified through an EDFA before being demultiplexed using a CWDM *with* 200 GHz *channel spacing*. The modulated carrier at 1551.8 nm was delayed relative to the other carrier by passing it through a tunable optical

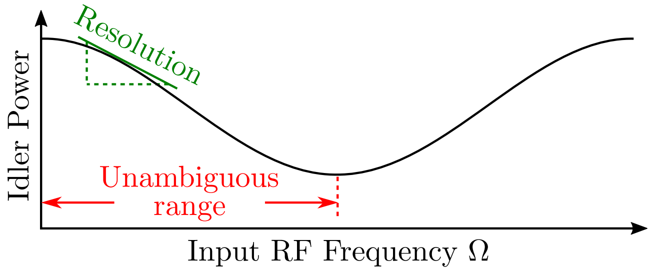

Fig. 2. Average idler power as a function of unknown RF frequency.