Optical frequency comb based system for photonic refractive index sensor interrogation

MARKUS KNOERZER,1,4 CRISPIN SZYDZIK,1,2 GUANGHUI REN,1
CESAR S. HUERTAS,1 SONYA PALMER,1 PHUONG TANG,1 THACH
G. NGUYEN,1 LAM BUI,3 ANDREAS BOES,1 AND ARNAN
MITCHELL1,5

1School of Engineering, RMIT University, GPO Box 2476, Melbourne, Victoria 3001, Australia
2The Australian Centre for Blood Diseases, Monash University, Alfred Medical Research and Educational
Precinct, 99 Commercial Road, Melbourne, Victoria, 3004, Australia
3School of Engineering and Technology, Central Queensland University, 120 Spencer Street, Melbourne,
VIC 3000, Australia
4markus.knoerzer@student.rmit.edu.au
5arnan.mitchell@rmit.edu.au

Abstract: In this contribution, we demonstrate how an optical frequency comb can be used
to enhance the functionality of an integrated photonic biosensor platform. We show that if an
optical frequency comb is used to sample the spectral response of a Mach-Zehnder interferometer
and if the line spacing is arranged to sample the periodic response at 120° intervals, then it is
possible to combine these samples into a single measurement of the interferometer phase. This
phasemeasurementapproachisaccurate, independent of the bias of the interferometer and robust
against intensity fluctuations that are common to each of the comb lines. We demonstrate this
approach with a simple silicon photonic interferometric refractive index sensor and show that
the benefits of our approach can be obtained without degrading the lower limit of detection of
3.70×10−7 RIU.

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1. Introduction

Optical frequency combs have revolutionized many fields in science, some of the most prominent
of these are high-precision spectroscopy [1–3], time and frequency metrology [4] and optical
clocks [4,5]. An attractive way of generating frequency combs uses high Q resonators where an
excited resonance could induce oscillation on neighboring resonances through Kerr nonlinearities.
Recently it has been shown that combs with mutually coherent lines can be achieved via the
excitation of so-called soliton crystals [6]. An alternate approach to achieving coherent combs is
the use of electro-optic phase modulation [7]. These highly phase stable combs are emerging as
the basis of next generation high capacity communications systems [8] and dual comb techniques
for spectral chemical analysis [9].

The emergence of comb based spectral analysis systems presents opportunities for other fields
where spectra must be interrogated with high precision. One possible application could be the
optical readout of integrated photonic biosensors. These types of biosensors aim to provide
laboratory quality chemical and biological analysis in a low-cost, miniaturised integrated chip,
showing great potential for the development of point-of-care (PoC) tests [10]. Their multiplexing
capabilities even allow measurement of multiple targets in parallel [11].

The underlying working principle of integrated photonic biosensors is based on evanescent
field sensing. The evanescent field describes the part of the optical waveguide mode field that
is outside of the waveguide core and can therefore interact with the surrounding media. In
these biosensors, the surface of the waveguide is usually functionalised with a biorecognition
element (such as antibody, nucleic acid or enzyme) that recognizes with high specificity an analyte of interest. This biointeraction causes a change of the refractive index at the waveguide surface, which through interaction with the evanescent field manifests in a change of the effective refractive index of the waveguide mode [12]. Changes in the effective refractive index can be measured very precisely with resonant or interferometric structures. Resonant structures, such as micro ring resonators (MRR), change their resonant wavelength [13,14]. In interferometric structures, such as Mach-Zehnder Interferometers (MZI) or bimodal waveguides (BiMW), the change in the effective refractive index causes a phase delay in one arm or mode respectively, which can be measured as an intensity change at the output [15]. Interferometric biosensors have attracted significant attention as they offer among the highest sensitivities in the field [15,16]. Their sensitivity scales linearly with size and so large sensing lengths can lead to greatly enhanced sensitivities.

Integrated photonic biosensors are very attractive for detecting trace amounts of biomolecules as they can monitor their presence in samples in real-time without the need of any labelling procedure [17]. Monitoring in real-time is in sharp contrast to currently used laboratory tests for biological elements requiring methods such as enzyme-linked immunosorbent assay (ELISA), polymerase chain reaction (PCR) and cell cultures, which require several hours to days [15]. Integrated photonic biosensors have been used to detect proteins [18,19], bacteria [20] as well as micro-RNA sequences [21]. Other promising fields are drug discovery [22] and environmental monitoring [23]. These sensors have achieved extremely high sensitivities in the region of $10^{-9}$ to $10^{-8}$ RIU for bulk sensitivity [15,24] and are in the fg/mm$^2$ region for surface sensing in a direct assay [12], eluding the need for secondary antibody recognition such as the gold standard ELISA [25]. The potential for highly precise and very rapid sensing is critical for point-of-care devices and can also greatly improve the throughput and flexibility of drug discovery platforms [26,27].

A key drawback of interferometers is that they exhibit a dynamic spectral response which is strongly dependent on the reference phase difference between the sensing and reference arms. Typically, an interferometer should be biased for maximum sensitivity at the quadrature point, but bias drifts (e.g. due to temperature) or very large signals can result in the bias of the interferometer shifting to a peak or a null of the spectral response where the sensitivity vanishes. Furthermore, a typical interferometer maps output power to phase between the sensing and reference arms. Hence it is difficult to distinguish between fluctuations in the intensity of the light being used to probe the sensor and genuine changes in the analyte under test.

There have been several approaches to overcome this limitation with the use of different forms of modulation, such as serrodyne modulation [28], phase-generated-carrier demodulation [29] or by looking at higher order harmonics of a phase modulated optical carrier [30]. All these techniques require a precise adjustment of the modulation amplitude either to ensure a sweep over exactly one period [28] or that two terms of the Bessel function are equal [29,30]. This requires a precise calibration step prior to the measurement. Another approach to extract a linear signal change for bulk refractive index sensing has recently been demonstrated by using an interferometer with 120° phase difference [31,32]. The reported implementation achieved a three-port output with 120° phase difference by using a specifically designed multi-mode interference (MMI) combiner. However, it was found that the system performance was highly dependent on fabrication tolerances and that a calibration step was required to account for variations between instances of nominally identical devices [33]. Furthermore, this structure increases the number of optical output ports from one to three. This makes the alignment of detectors or fibres more cumbersome and prone to false extraction of signal readings, for example if a misalignment of a single detector or fibre occurs at the output.

In this paper we show that a simple silicon photonic Mach-Zehnder refractive index sensor with a single input and a single output can be probed with an optical frequency comb source to
achieve similar functionality to [33], eliminating the stringent fabrication tolerances. We use an electro-optic frequency comb and adjust the comb spacing to sample the interferometer spectral response at 120° intervals. By monitoring the transmission response of three of these comb lines it is possible to extract the relative phase between the arms of the interferometer independent of the bias point of the interferometer or the intensity of the optical carrier. This method provides a flexible approach that can be applied to any interferometers and could be combined with other signal processing techniques to achieve a robust and precise sensing platform.

2. Methods

2.1. Concept

Figure 1 presents a diagram of our system configuration. Figure 1(a) illustrates a typical MZI sensor and interrogation platform. A single CW laser line is transmitted through the sensor and the transmitted power is recorded. To calibrate, the laser wavelength is swept to reveal the sinusoidal transmission response of the MZI. The wavelength is then set to the quadrature point (where the power is half way between maximum and minimum), and then the analyte measurement is conducted. For small signals one can then assume a linear response between the detected power and the phase change. However, in the case of a large signal (as illustrated in the inset) or a drift in the bias, the mapping between the phase and the intensity is nonlinear due to the sinusoidal transfer function of the sensor, requiring a manual readout. This nonlinearity makes the traditional biosensor platform difficult to use reliably, being vulnerable to bias drifts and having limited dynamic range.

Our proposed approach is illustrated in Fig. 1(b), here an optical frequency comb is transmitted through the same MZI sensor as used for the conventional phase extraction method. Of the transmitted spectrum three comb lines are split into three optical channels and recorded by individual photodetectors. The line separation depends on the free spectral range of the used interferometer. These three wavelengths sample the spectral response of the interferometer at multiple of 120° intervals, as can be seen in the insets. The vector sum of these three signals allows continuous recovery of the phase shift between the interferometer arms. This method does not require a calibration step prior to the measurement and offers a linear sensitivity, independent of the bias.

2.2. Experimental implementation

Our experimental implementation is presented in Fig. 2. A microscope image of the photonic chip biosensor is presented in the inset of Fig. 2(a). It consists of an asymmetric Mach-Zehnder Interferometer (AMZI) with adiabatic couplers as splitter and combiner. The waveguides have a width of 450 nm and a height of 220 nm, and are single mode for Transverse Electric (TE) polarization. The adiabatic couplers are 350 μm long and the two arms taper from 450 nm to 400 nm and 500 nm, respectively. In our sensor, the sensing arm is 4.99 mm long, while the reference arm is only 0.30 mm long, leading to an arm length difference of 4.69 mm. The sensor layout contains 24 sensors and has a total size of 5 by 10 mm. The entire photonic chip has a size of 15 by 15 mm, to accommodate the microfluidic fluid handling as well. Our sensor is fabricated on a silicon-on-insulator platform. It is patterned using electron-beam-lithography (EBL) and etched using reactive ion etching (RIE). The optical interfaces are vertical grating couplers, with a loss of about 5 dB each, which are probed by single mode fibers. The fibers are mounted in a custom assembly enabling interface at 10 degrees from vertical, but also providing microscope access from the top.

Figure 2(a) presents the experimental system including a microfluidic chip assembly used for sample fluid handling. This microfluidic device includes fluid reservoirs, pneumatically actuated on-chip valves and micropumps, which allow automatic control of our refractive index references
Fig. 1. (a) Principle of the conventional single wavelength phase extraction method: A CW single mode laser is sent through a photonic chip and the transmitted power is detected by a photodetector (PD) and recorded over time. For a change in refractive index the spectrum shifts (from dotted to dashed line). From the recorded transmission power over time values, the phase is extracted manually. Due to the non-linear response this manual conversion step causes a small error. (b) Principle of the proposed comb sensing setup: An optical frequency comb is sent through the photonic chip. Three comb lines are split into three channels by a demultiplexer, before being detected by three photodetectors (PD) and recorded over time. For a change in refractive index the same shift occurs, but now we measure at three different points at multiple of 120° intervals. All three recorded transmission power over time values are combined as a vector sum and the angle of the resulting phasor is the phase we want to extract.
Fig. 2. (a) Photograph of the assembled sensor setup including the Polydimethylsiloxane (PDMS) microfluidic system with an integrated on-chip pump, as well as the fiber coupling. The insets show a microscope picture of the photonic chip and the asymmetric Mach-Zehnder Interferometer (AMZI). (b) Implementation of the electro-optic comb sensor: The CW single laser line is modulated with a phase modulator (PM) by a radio frequency (RF) and amplified with an erbium-doped fiber amplifier (EDFA) before being interfaced to an AMZI. The transmitted signal is amplified with an EDFA, split into three channels by a WaveShaper (WS) and detected by three photodetectors and quantized with a data acquisition system (NI-DAQ). (c) Spectrum of the phase modulated single mode laser before the EDFA. The modulation amplitude is chosen to achieve approximately similar height for the first side-bands and the carrier. (d) Comb transmission spectrum through the AMZI. The three comb lines are sampling three points of the spectrum of the AMZI.
and eventually reagents for biosensing. This microfluidic system is based on previous work by our research group, further details can be found in [34].

The photonic sensor assembly is mounted on a custom-made sample holder and is temperature stabilized using a Peltier element and a temperature controller (ILX Lightwave LDT-5412), to reduce temperature drifts of the sensor signal due to the temperature sensitivity of the AMZI, which is $-3.84 \text{rad/}°\text{C}$ at the operation temperature of 22.8 °C.

Figure 2(b) presents an illustration of how our interrogation system is implemented. We use a thermally tuned External Cavity Diode Laser (Coherent Solutions LaserBlade, C band) with a linewidth of $<100 \text{kHz}$ and 10.9 dBm output power. The frequency comb source is implemented using and electro-optic phase modulator similar to [7]. After transmission through the sensor chip, three of the comb lines are separated using a wavelength selective switch (WSS, Finisar WaveShaper 4000S) and each signal is routed to an independent photodetector (Monitor output of Thorlabs PDB 460C-AC, BW 1 MHz, Responsivity 1 A/W, Gain 10 V/mW). The three responses are then combined numerically to achieve a measurement of the phase on the MZI.

The RF frequency input to the phase modulator of the electro-optic frequency comb source determines the free spectral range (FSR) of the optical frequency comb. We use a broadband modulator (EOSpace PM-5V4S-40), a tunable RF source (Anritsu MG3694A) and an RF amplifier (SHF 803P) that all can operate up to 40 GHz.

As the FSR of the comb is tunable, we can adjust it to sample the spectral response of the MZI sensor chip at a defined period. The free spectral range of our sensor chip is:

$$\Delta \lambda_{FSR} = \frac{\lambda^2}{n_g \cdot \Delta L} = \frac{(1550 \text{nm})^2}{4.36 \cdot 4.69 \text{mm}} = 0.1174 \text{nm}$$

$$f_{FSR} = \frac{c \cdot \Delta \lambda_{FSR}}{\lambda \cdot (\lambda + \Delta \lambda_{FSR})} = 14.653 \text{GHz}$$

Where $\Delta \lambda_{FSR}$ is the free spectral range, $\lambda$ is the carrier wavelength, $n_g$ is the group refractive index, $\Delta L$ is the path length difference between the two arms of the MZI, $f_{FSR}$ is the corresponding frequency of the free spectral range and $c$ is the speed of light.

To achieve our robust sampling approach, we wish to set the comb spacing to sample the spectral response of the MZI at 1/3 of its period, or 4.88 GHz or 0.0391 nm. However, the spacing of these comb lines must be sufficient that they can be separated by the WSS. The WSS has a minimum resolution of 12.5 GHz. This requires us to distribute our samples across more than one period of the MZI. We set the carrier wavelength to 1550.0 nm, and the modulation frequency $f_{RF} = \frac{7}{3} f_{FSR} = 24.421 \text{GHz}$.

The modulation amplitude is adjusted to achieve approximately similar height for the first side-bands and the carrier. The spectrum of the resulting comb is shown in Fig. 2(c) and has a total optical power of 7.3 dBm and approximately 0.5 dBm for each of the inner three comb lines. Before interfacing to the photonic chip, the optical signal is amplified with an erbium-doped fiber amplifier (EDFA, OZ Optics) to approximately 20 dBm. The transmitted comb spectrum after the photonic chip has an optical power of approximately $-12 \text{dBm}$ and is shown in Fig. 2(d). The shown three comb lines are sampling the spectrum of the asymmetric Mach-Zehnder Interferometer (AMZI) at three points.

To use the full input range of the used analog-to-digital converter (ADC, NI-9215, ±10 V, 16 bit) we used a second EDFA (Fullwell) to amplify the optical signal to 10 dBm. Alternatively, one could use photodetectors with adjustable gain. The three transmission measurements were separated using the WSS, detected using independent photodetectors and quantized using a multi-channel ADC at a sample rate of 1000 samples/s. The values are normalized to a range of 0 to 1, to compensate for slightly different transmission losses through the individual optical channels. The vector sum of the three normalized power values ($P_1$, $P_2$ and $P_3$) yield a phasor $s$. 
This phasor $s$ can be calculated using the equations provided in [32,33]:

\[
\begin{align*}
x &= P_2 - 0.5 \cdot P_1 - 0.5 \cdot P_3 \\
y &= \sqrt{3} \cdot \frac{1}{2} (P_1 - P_3) \\
s &= x + jy
\end{align*}
\]

The argument of $s$ is the phase we want to extract.

The above described comb sampling phase extraction method is compared to the conventional single wavelength phase extraction method for reference. The setup presented in Fig. 2(b) can also be used for the conventional phase extraction, by turning the modulation off and only recording the central channel. This changes the setup to a single wavelength configuration.

For the single wavelength method, one must perform a wavelength sweep before each measurement in order to determine the wavelength of the quadrature point, as well as the maximum and minimum transmission power. After this calibration step, the laser is set to this wavelength and the transmission power is recorded over time, before being normalized to the maximum and minimum transmission power. A change from maxima to minima is equivalent to a phase change of $\pi$. The baseline will be at 0.5, if the quadrature point was chosen correctly. When the sensor is exposed to the analyte, the output level will change. The signal with the analyte present is subtracted from the baseline to obtain the induced phase change. This method assumes a linear relation between the signal power and induced phase change which is only true for small changes and when the sensor is biased at the quadrature point.

3. Results and discussion

In this section we compare the conventional phase extraction when using only one wavelength with the proposed comb sampling phase extraction method. Specifically, we look at the responsivity for large signals (Section 3.1), the robustness against bias drift (Section 3.2) and the common-mode rejection (Section 3.3).

3.1. Responsivity for large signals

Two important figures of merit for biosensors are sensitivity and lower limit of detection (LoD). To characterize the sensitivity of our sensor for large signals, we use the microfluidic system to apply deionised (DI) water and different Sodium Chloride (NaCl) solutions, with concentrations of 3, 6, 9 and 12%, to the sensor surface. The refractive index of different concentrations is calculated based on the weight percentage of NaCl in DI water [35].

The top part of Fig. 3(a) shows the recorded raw signals for the three channels, when transitioning from DI water to a 3% NaCl solution and back to DI water. Each fluidic sample measurement is 120 s long, before changing back to the buffer (as can be seen in Fig. 3(a)). The signals change by approximately $4.6\pi$ rad or 14.57 rad, as a change from maxima to minima of the sensor’s signal is equivalent to a phase change of $\pi$. The extracted phase for the comb sampling method can be seen in the bottom part of Fig. 3(a). Unlike the conventional phase extraction method, it is a continuous and linear phase readout.

Figure 3(b) presents the extracted phase changes for the different NaCl solutions, compared to the conventional single wavelength method and the simulation. Both experiments show good linearity and intercept with the origin. The sensitivity is determined by the slope of the phase change per refractive index unit. The extracted sensitivity is 3097 rad/RIU and 3108 rad/RIU for the single wavelength and the comb sampling method, respectively. The observation that both phase extraction methods give very close results is as expected and can be explained by the fact that the phase response of the interferometer is the same for both methods. The only difference is that we are considering three signals to extract the phase opposed to only one for the
Fig. 3. (a) Raw signal of the detected power levels as a function of time for a fluid transition from DI water to 3% NaCl solution and back. This corresponds to a change in refractive index of 0.005 RIU. (b) Extracted phase changes for the different NaCl solutions. Both methods show good linearity and intercept with the origin. The extracted sensitivity is 3097 rad/RIU and 3109 rad/RIU for the single wavelength and the comb sampling method, respectively. The measured sensor sensitivity was lower than the simulated sensitivity of 3750 rad/RIU. (c) The noise on the phase measurement signal is 0.0962 rad and 0.0416 rad for the single wavelength and the comb sampling method, respectively. (d) Histogram of the single wavelength phase measurement. (e) Histogram of the comb sampling phase measurement.

For comparison, we simulated the sensitivity using an eigenmode solver for different cladding refractive indices and calculated the phase difference at the output based on the change in the effective refractive index in the measurement arm. The predicted sensitivity of 3750 rad/RIU is higher than the measured ones. The difference between the simulated and the measured sensitivity might be caused by an oxide layer on the sensor surface or by small variations of the refractive index of the experimental NaCl solutions.

The noise is calculated by taking three times the standard deviation of 60 s unfiltered data of a flat baseline (DI water) with the on-chip pump running. For the conventional single wavelength method, the noise is 0.0962 rad and 0.0416 rad for the comb sampling method (see Figs. 3(c)–(e)). One possible explanation for the lower noise of the comb sampling method is the increased stability of the system and its common-mode rejection (see Section 3.3).

The corresponding lower limit of detection (LoD) is $3.10 \times 10^{-5}$ RIU for the single wavelength method and $1.34 \times 10^{-5}$ RIU for the comb sampling method. The use of filtering can greatly decrease the noise level and hence increase the LoD. To illustrate the effectiveness of filtering, we applied a digital running average filter on the extracted phase signal with a time window of 10000 samples (10 s) and 60000 samples (60 s), this reduces the noise levels to $6.86 \times 10^{-3}$ rad and $1.15 \times 10^{-3}$ rad, respectively. This improves the corresponding LoD of the comb sampling method to $2.21 \times 10^{-6}$ RIU for 10 s of filtering and $3.70 \times 10^{-7}$ RIU for 60 s of filtering. It is important to...
note, that filtering with such a wide time window can only be applied to signals which do not contain fringes, as they would be filtered out. For the conventional single wavelength method this is only the case for small sample concentrations, but for the comb sampling method it can be applied to any concentration, since the extracted phase signal does not contain fringes. Furthermore, the presence of very slow signal drifts (e.g. due to temperature) can be removed from the raw data, before applying digital filtering.

The comb sampling phase extraction method has the same sensitivity as the conventional single wavelength method, but without the cumbersome manual phase extraction step.

3.2. Robustness against bias drift

As described previously, the conventional single wavelength phase extraction method requires the laser wavelength to be at a quadrature point of the spectral response of the used interferometer. This requires a calibration step prior to each measurement and makes the measurement vulnerable to bias drift. In this section, we investigate how much phase change we detect for small signals, in case the wavelength is detuned from the quadrature point of the AMZI spectral response for the single wavelength method and compare it to the comb sampling phase extraction method. We used the microfluidic channels to apply DI water and a 0.05% NaCl solution to the sensor surface. The detuning from the quadrature point is achieved by slightly changing the wavelength of the laser.

Figure 4(a) shows the measured phase change for the same sample as a function of the detuning of the interferometer, where 0.5\(\pi\) rad corresponds to the quadrature point. For the traditional single wavelength method, the strongest and most accurate phase change can be measured at the quadrature point of the spectral response. The more detuned the MZI is from the quadrature point, the less phase change is measured for the same small sample concentration. On the other hand, the measured phase change of the comb sampling method is independent of the detuning, as can be seen by the constant phase change shown in Fig. 4(a). Only at the quadrature point both methods measure the same phase change for the same sample.

This behaviour can be explained by drawing from the analogy of a circle in a complex plane as it is depicted in Figs. 4(b) and 4(c). The comb sampling method computes a phasor \(s\) (indicated by the blue arrow). The angle of the phasor corresponds to the phase that we want to extract and since we can compute the phasor, we can calculate relative phase changes of the phasor regardless of its absolute angle. This is not the case for the single wavelength method. Here, we only measure the projection of the phasor on the real axis of the complex plane. The variations of the projected amplitude depend strongly on the absolute phase of the phasor. Figure 4(b) illustrates a case, where the phasor is nearly parallel to the real axis. Small changes to the angle of the phasor will therefore only cause very small changes in the amplitude of the real part (red arrow). Conversely, when the bias is shifted by 90\(\degree\) as shown in Fig. 4(c), a small change in the phasor’s angle (blue arrow) causes a large change of the real part (red arrow). This is the reason why one needs to operate the single wavelength phase extraction method at the quadrature point. This can be cumbersome and impractical to maintain. For the comb sampling phase extraction method this is not the case and one can chose any wavelength or detuning and get the same sensitivity for small signal changes, making it more convenient and reliable to operate.

3.3. Common-mode rejection

In this section, we compare the single wavelength and comb sampling phase extraction method for common-mode rejection. We investigate how strongly the extracted phase signal is influenced by transmission power changes that are not caused by the operation of the sensor. Examples of factors that could influence the transmitted power could be fluctuations of the laser power or slight misalignment/vibrations of the fiber coupling to the photonic chip.
For the conventional single wavelength phase extraction method, the recorded phase change for the same sample (0.05% NaCl) depends on the detuning of the Mach-Zehnder Interferometer from the quadrature point. If the sensor is biased at a quadrature point (0.5π rad), where the spectral response has the highest slope, the single wavelength and the comb sampling method measure the same phase change for the same sample. The measured phase change decreases towards the extrema for the single wavelength method, while the comb sampling method has a constant reading independent of the bias point. (b) For a phase shift (blue arrows) close to the maximum of the real signal, the change of the real part (red arrow) is only small. There is close to no step visible in the measurement over time (see inset). (c) Around the quadrature point, the change on the real axis is the greatest, and the measurement over time shows the expected step (see inset).

The working principle of the common-mode rejection is similar to the one for bias point robustness described in the previous section. This principle is illustrated in Figs. 5(a)–5(e). The comb sampling phase extraction method combines three measured power values as a vector sum and the phase angle of the resulting phasor $\mathbf{s}$ is the phase value we want to extract. If a change in signal amplitude occurs (for example due to optical alignment, or laser power fluctuation), all three channels will experience the same change in amplitude.

This results in a change of the amplitude of the phasor $\mathbf{s}$ (indicated by the blue circle), while its phase angle remains unaffected, see Figs. 5(b) and 5(c). The single wavelength method on the other hand relies on the projection of the phasor $\mathbf{s}$ onto the real axis (red arrow), as can be seen in Figs. 5(d) and 5(e). Any changes in amplitude of the optical carrier are indistinguishable from changes in phase. Hence the single wavelength phase extraction method is vulnerable to common-mode noise and instability.

We experimentally tested the common mode rejection by adding a variable optical attenuator before the photonic chip and adjusting the optical power that is coupled to the chip. We changed the input power stepwise as shown in the top graph of Fig. 5(f) and the resulting stepwise changes in output power level of the three wavelengths are shown in the subfigure below. The bottom graph of Fig. 5(f) shows the extracted phase as a function of time for the comb sampling method. It can be seen that the extracted phase remains unaffected for reductions of less than 50% of the initial input power. Both phase extraction methods are applied to this data and the resulting phase changes are presented in Fig. 5(g). The small changes of the comb sampling method can be explained by small asymmetries of the spectral response of the used AMZI (see Fig. 2(d)). Ideally the spectral response would be symmetrical, and all peaks would have the same height. The effect of even larger power changes is investigated and shown in Fig. 5(h). While the conventional method loses the signal quickly at about −5 dB, the comb sampling method increases very little until a power reduction of about 50 dB where the attenuation becomes too
Fig. 5. (a) For the comb sampling method, the three measured power values have a relative phase difference of 120° to each other. (b) The vector sum of the three measured signals yield the phasor s, illustrated in blue. (c) With half power on all three measured signals the extracted phasor has half the amplitude, but the same angle. (d) For the single wavelength phase extraction method, one only measures the projection of the phasor onto the real axis (indicated by the red arrow). (e) Changes in signal amplitude will directly affect the measured real part. Measurements: (f) For changes in input power (top) the power levels at the three outputs change accordingly (middle). The effects on the readout for the comb sampling method (bottom) become only significant once the input power drops by 50% or more of its original value. (indicated with the light grey background) (g) The extracted phase for the single wavelength method, using only data from channel 2, changes linearly with the input power as expected, while the extracted phase of the comb sampling method remains almost flat. (h) For large changes of the input power the single wavelength method loses the signal after about −5 dB, while the extracted phase with the comb sampling method remains quite constant until about −50 dB signal change.
strong and the measured power values disappear into the noise floor, which is indicated by the blue dotted line. The slope of the single wavelength method (red line) is 0.595 rad/dB, while for the comb sampling method (blue line) it is $-0.005$ rad/dB. This means the comb sampling phase extraction method is suppressing common-mode noise by a factor of 119, compared to the single wavelength phase extraction method.

Limiting factors of the comb sampling phase extraction method are the small asymmetry of the spectral response of the used AMZI, as can be seen in Fig. 2(d), and the dynamic range of the used detectors, as can be seen in Fig. 5(h).

4. Conclusion
We have presented a comb sampling method for phase extraction of a typical asymmetric Mach–Zehnder interferometer sensor. The comb is generated by phase modulating a CW carrier and the RF frequency is adjusted to sample the free-spectral range of the used sensor at multiple of $120^\circ$ intervals. We characterized the comb sampling phase extraction method for large signals and showed it has the same sensitivity as the conventional single wavelength method but eliminates the cumbersome manual phase extraction step and offers a continuous and linear phase readout, which makes this method more convenient to use. We found that for small signals the measured phase response of the comb sampling method is linear and independent of the interferometer bias point, which is a great advantage over the conventional single wavelength method, which should only be used around the quadrature point. Furthermore, we found that the comb sampling phase extraction method provides common-mode rejection. This makes this technique more robust against common-mode variations and noise in the optical power compared to the conventional single wavelength phase extraction method. Our approach advances the frontier beyond recent demonstration using three output interferometers with the specific advantage of being applicable to any pre-existing interferometer topology that has a periodic response and does not require any physical modifications of the sensor design, such as adding multiport couplers at the input or output. This technique can thus be a drop-in alternative to the conventional single wavelength method, which is currently widely used.

Future work will investigate the impact of systematic asymmetries in the interferometer response and methods to mitigate associated measurement errors. We will also explore implementation of more sophisticated photonic signal processing and noise reduction techniques enabled by this platform with the aim of achieving greatly improved sensitivity without sacrificing robustness, simplicity and easy interfacing.

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