Development of a Waveguide-Based Interferometer for the Measurement of Trace Substances

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ABSTRACT

Photonic integration on a chip has the potential to develop new low-cost, high-performance sensing devices [1, 2]. A proof of concept of the sensing capabilities of a waveguide-based photothermal interferometer for the measurement of traces of light-absorbing substances (soot particles, gases) has been achieved. The measurement principle can also be extended to a wide range of other applications such as refractive index measurements, or vibration/distance sensors. A unique feature is that the waveguide technology allows for a passive operation of the interferometer, i.e., no quadrature point control is required.

KEYWORDS: photonic integrated circuits, interferometry, optical sensing

INTRODUCTION

Waveguide-based interferometers have the potential to offer several advantages over sensors using free-space optics. Because light is guided in waveguides, a high integration density is possible with the following potential benefits: no beam alignment, increased stability, comparable sensitivity, cost efficiency, and the ability to be miniaturized.

In addition, photonic-integrated-circuit (PIC) technology enables the development of photonic components that are either unavailable or difficult to realize in free space. One such key component is the 2x3 coupler. In conventional two-output interferometers, the sensitivity is highly dependent on the interferometric phase - at the extremes (full constructive/destructive interference) the sensitivity is zero. This requires a complex tracking and control of a "quadrature point". By using beam recombination optics with 3 outputs, the signal fading is significantly reduced and the interferometer can be operated passively, without quadrature point control.

RESULTS

Figure 1 illustrates one of the major advantages of using a 2x3 coupler in an interferometer: The operating point is not controlled during this experiment, and the interferometric phase varies freely. Since the 3 outputs are phase-shifted by approximately 0°, 120°, and 240°, the system can be operated passively in a defined manner. The overall sensitivity, calculated from the three response curves, lies between 0.5 and 1.2 V/rad.

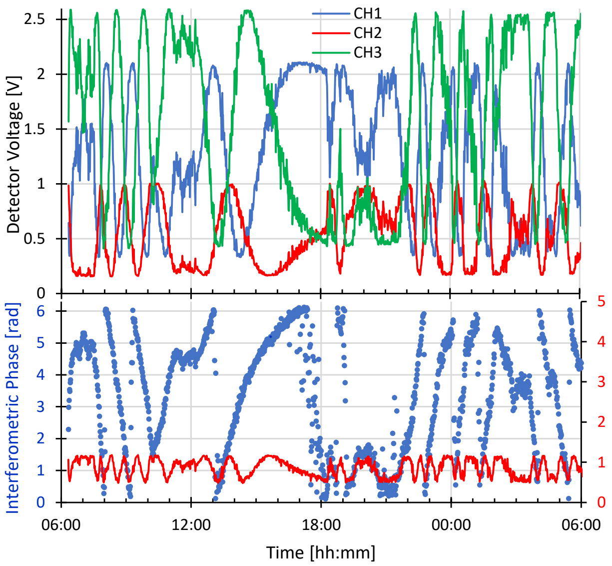

Figure 1: 24-hour measurement of interferometric signals, aggregated to 1-minute averages. Top: the measured light intensities at the 3 outputs of the interferometer using a multi-mode interferometer (MMI) as recombiner. Bottom: the derived interferometric phase and the phase-dependent sensitivity.

We have used a waveguide-based interferometer setup for the quantitative measurement of trace substances via the photothermal effect, where specific trace gases, soot particles, or dissolved molecules in liquids are detected and quantified by their light absorption: When a modulated pump light beam crosses the interferometer beam in the analyte, the absorbed pump energy causes a tiny local temperature increase in the sample, resulting in a change in the refractive index of the analyte and thus a differential change in the effective optical path length in the arms of the interferometer. The amplitude of the measured phase modulation is proportional to the absorption coefficient of the sample. Knowing the geometry and power of the pump beam, the concentration of the absorbing trace substance can be inferred [3].

Our setup is not yet highly integrated - we use a fused fiber coupler as a beam splitter and a PIC-based MMI as a recombiner [4]. The measuring chambers are connected to the couplers by relatively long single-mode fibers, resulting in an optical path length of an interferometer arm of ≈ 70 cm. Nevertheless, with this setup we achieve a **detection limit of the interferometric phase of less than 1 microradian**.

When operated as a photothermal interferometer, this high sensitivity allows the detection of light-absorbing trace species: We achieve a detection limit in terms of absorption coefficient of about 10^{-4} m^{-1} (1σ, 60 s integration time). At our pump wavelength of 405 nm, this corresponds to a NO_2 concentration of about 1 ppm or a mass concentration of 10 $\mu g/m^3$ for submicrometer soot particles. An analysis [4] shows that the limiting noise component at the modulation frequency of 80 Hz is the interferometric phase noise resulting likely from the long fibers.

PLANNED FUTURE STEPS

The current setup offers much room for improvement: It can be significantly miniaturized, which has the added benefit of reducing the noise, resulting in improved sensitivity and stability. The detectors can also be placed directly on the same PIC (high integration). A simplified sketch of such a miniaturized photothermal interferometer is shown in Figure 2.

The added value of integrating individual interferometric components on a single PIC with a size of only a few millimeters can be extended to other sensor applications:
For example, the passively operated interferometer can be used as a distance or vibration sensor. The technology could also be used to monitor the refractive index of liquid media. Other new applications, such as in microfluidics are also considerable.

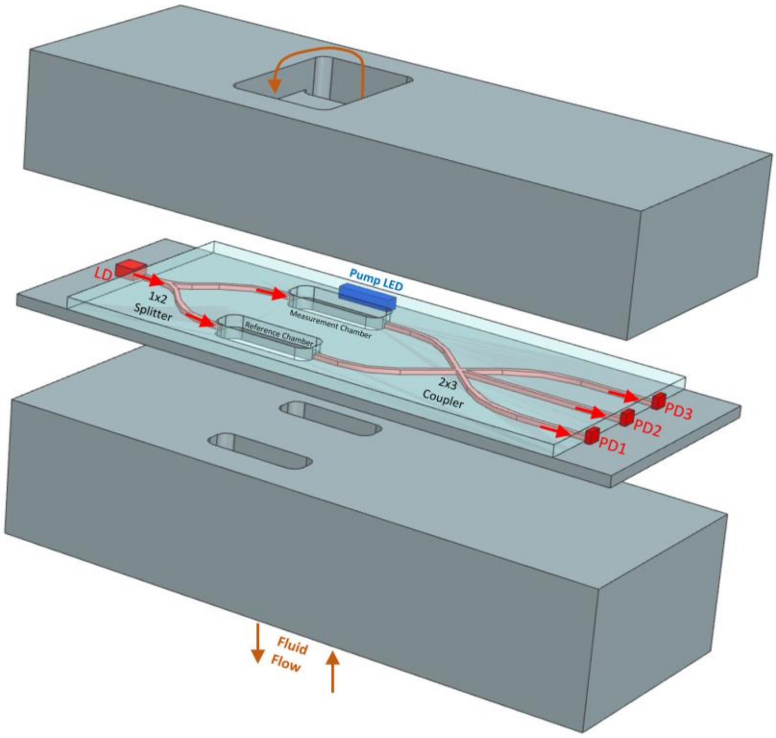

Figure 2: A vision of a miniaturized interferometer with the components integrated on a centimeter-sized photonic chip. The PIC in the center is sandwiched between housings with flow channels containing the analyte. The beam splitter and recombiner are located between the two measurement chambers. In one chamber, the photothermal effect is induced by pulsed light (e.g. with a blue LED). The probe laser (LD) and the three photodiodes (PD) are also integrated.

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