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On-chip high sensitivity laser frequency sensing with Brillouin mutually-modulated cross-gain modulation

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Abstract

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Keywords

cross, modulation, modulated, gain, mutually, brillouin, sensing, frequency, laser, sensitivity, high, chip

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On-chip high sensitivity laser frequency sensing with Brillouin mutually-modulated cross-gain modulation

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Abstract: We report the first demonstration of a photonic-chip laser frequency sensor using Brillouin mutually-modulated cross-gain modulation (MMXGM). A large sensitivity (~ 9.5 mrad/kHz) of the modulation phase shift to probe carrier frequency is demonstrated at a modulation frequency of 50 kHz using Brillouin MMXGM in a ~ 7 cm long chalcogenide rib waveguide.

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1. Introduction

Devices with large spectral sensitivity are becoming increasingly desirable in applications such as metrology, optical sensing, quantum information processing, and biomedical engineering [1–4]. Although the spectral sensitivity can be enhanced using slow light [5, 6], the central measurement is usually that of the optical phase, and therefore requires the use of an interferometer. Recently, Sternklar et al. exploited a novel slow-light configuration known as Brillouin mutually-modulated cross-gain modulation (MMXGM). In this configuration, both a pump and Stokes signal are modulated at the same frequency; the Brillouin gain then introduces higher harmonics to the Stokes signal, with the first harmonic possessing a phase delay that is extremely sensitive to the value of the gain. By measuring the phase delay of the first harmonic, an extremely sensitive measurement of the detuning of the Stokes shift may be obtained. This technique relies on the gain associated with the Brillouin resonance rather than the dispersion, and so differs from frequency measurements that directly exploit the presence of slow- and fast-light near an SBS resonance [7–14]. With such a configuration, an impressive spectral sensitivity ~ 6.5 mrad/kHz in the modulation phase was achieved for a modulation frequency of 100 Hz in a 3km long optical fiber [15]. The striking feature of this configuration is that it does not require an interferometer: the spectral sensitivity is enhanced in the modulation phase rather than the optical phase, which makes it convenient for many optical applications.

Recently, on-chip stimulated Brillouin scattering was demonstrated using the large Brillouin scattering cross-section ($g_B = 0.74 \times 10^{-9}$ m/W), small effective mode area ($A_{eff} = 2.3 \mu\text{m}^2$) and strong light-sound confinement in a ~ 7 cm chalcogenide (As_2S_3) rib waveguide [16]. Here, we report the first demonstration of photonic-chip laser frequency sensing using Brillouin MMXGM. For our on-chip Brillouin MMXGM demonstration a large spectral sensitivity of ~ 9.5 mrad/kHz was measured for a modulation frequency of 50 kHz - this absolute sensitivity is comparable to the previous MMXGM-based measurements in kilometers of fiber. It has been noted in previous work, that provided the phase shift between the pump and Stokes signal can be made exactly equal to π radians, the sensitivity is inversely proportional to the length of the gain medium [15]. This suggests that on-chip devices that use Brillouin MMXGM can potentially be used to significantly enhance the achievable sensitivity. On-chip implementation of Brillouin MMXGM is also desirable from the point of view of the creation of compact on-chip

integrated photonics devices. We discuss here the dependence of the sensitivity on the device length as well as on deviation from the phase shift of π , and show that the maximum spectral sensitivity is also limited by the resolution achievable in controlling the phase of the modulated Stokes signal.

2. Principle and theory

Figure 1 shows the concept of laser frequency sensing using Brillouin MMXGM in a chalcogenide (As_2S_3) photonic-chip [17, 18]. A pump (ω_p) and a Stokes signal (ω_s) are both modulated at the same frequency $f_{mod} \ll f_{Brillouin}$ and are counter-propagated through the chip. If the frequency difference between pump and Stokes signals is close to the Brillouin resonant frequency $f_{Brillouin}$ then the Stokes will experience Brillouin gain, and will undergo selective amplification at the points where the peaks of the modulated pump coincide with the troughs of the modulated Stokes. This effect distorts the Stokes wave and introduces higher harmonics. The first harmonic wave possesses a phase delay which is extremely sensitive to the detuning from the Brillouin resonance. It is important to note that the phase modulation due to MMXGM is fundamentally different from the phase changes induced by the dispersion of SBS, and can be made extremely sensitive to frequency detuning.

Fig. 1. MMXGM in the SBS medium. Both pump and signal are intensity modulated and the modulation phase shift at the front (left) facet is φ_2 .

The theory and principle of laser frequency sensing using Brillouin MMXGM has been previously derived in [14], for the specific case in which the modulation phase difference φ_2 between pump and Stokes is equal to π . In the following we give an outline of this theory, both to clarify the underlying physics and also to discuss the effects of deviations of φ_2 from the exact value of π .

Assuming a modulation depth of α for the pump signal, the pump intensity $I_1(z, t)$ can be written at the end of the waveguide ($z = L$) as:

$$I_1(L, t) = I_1^0 [1 + \alpha \cos(KL + \Omega t)], \quad (1)$$

where $\Omega = 2\pi f_{mod}$ is the angular modulation frequency and $K = \Omega n/c$ is the modulation wavenumber for a waveguide with effective index n . The Stokes signal is modulated with modulation depth β . At the front facet ($z = 0$) the intensity $I_2(z, t)$ of the modulated Stokes is:

$$I_2(0, t) = I_2^0 [1 + \beta \cos(-\varphi_2 - \Omega t)], \quad (2)$$

where φ_2 is the modulation phase shift between the pump and the Stokes signals at the front facet of the sample as shown in Fig. 1. As it propagates through the waveguide the Stokes signal

experiences Brillouin gain. Under the approximation that the pump is undepleted, at the output facet ($z = L$) the Stokes signal can be written [14]:

$$I_2(z = L, t) = I_2^0 [1 + \beta \cos(KL - \Omega t - \varphi_2)] \exp[G + \alpha G \text{sinc}(KL) \cos(\Omega t)], \quad (3)$$

where the gain G depends on detuning $\delta\omega_s$ from the Brillouin maximum according to the Lorentzian function:

$$G = G_0 [1 + (\frac{2\delta\omega_s}{\Gamma_B})^2]^{-1}, \quad (4)$$

where $G_0 = g_B I_1^0 L$ is the peak gain and Γ_B is the Brillouin linewidth, which is typically on the order of 10-50 MHz in most optical materials.

The expression for the amplified Stokes can be expressed equivalently as a sum of harmonics:

$$I_2(L, t) = i_{DC} + i_1 \cos(\theta_1 - \Omega t) + i_2 \cos(\theta_2 - 2\Omega t) + \dots \quad (5)$$

where the coefficients i_m ($m \geq 1$) and phases θ_m are functions of K , L , α , β , G and φ_2 . With weak modulation and $KL \ll 1$, Eq. (3) can be expanded as

$$I_2(L, t) \simeq I_2^0 \exp(G) [1 + \beta \cos(KL - \Omega t - \varphi_2) + \alpha G \text{sinc}(KL) \cos(\Omega t)]. \quad (6)$$

In Eq. (6), the terms on the right are the DC gain of the Stokes, the modulation from the Stokes and the modulation from the pump, respectively.

The total phase shift of the first harmonic θ_1 is

$$\theta_1 = KL + \tan^{-1} \left(\frac{\hat{G}KL + \sin(\varphi_2)}{-\cos(KL - \varphi_2) - \hat{G}} \right), \quad (7)$$

where $\hat{G} = G\alpha/\beta$. In Eq. (7), the KL term represents the linear phase delay across the propagation medium and the inverse tangent denotes the nonlinear phase delay that occurs as a result of Brillouin MMXGM. This effect depends on the detuning of the central Stokes peak from the center of the Brillouin resonance, as given by Eq. (4). This change in the gain will in turn advance or delay the phase of the first harmonic. The spectral sensitivity S depends directly on the change in the first-harmonic phase $\Delta\theta_1$ when there is a change in $\delta\omega_s$:

$$S := \frac{d\theta_1}{d(\delta\omega_s)} = \frac{d\theta_1}{d\hat{G}} \frac{d\hat{G}}{d(\delta\omega_s)} = \frac{-KL \cos \varphi_2 + \sin \varphi_2}{(\cos \varphi_2 + \hat{G})^2 + (\hat{G}KL + \sin \varphi_2)^2} \frac{d\hat{G}}{d(\delta\omega_s)}; \quad (8)$$

From Eq. (8) it can be seen that when $\varphi_2 = \pi$, the maximum sensitivity at $\hat{G} \approx 1$ will be inversely proportional to both L and f_{mod} , yielding the same result as previously derived in [14] and [15]. In principle, provided an exact phase modulation shift of $\varphi_2 = \pi$ can be reached, extremely high sensitivities can be attained by using short waveguides and low modulation frequencies. In practice, however, there is a limit to the resolution with which the modulation phase can be determined. We now consider the modulation phase shift to be close but not equal to π , such that $\varphi_2 = \pi + \delta\varphi_2$, where $\delta\varphi_2$ is small. Continuing the assumption that $KL \ll 1$, we find from Eq. (8) that the maximum sensitivity is

$$S_{\max} \approx \frac{1}{KL - \delta\varphi_2} \frac{d\hat{G}}{d(\delta\omega_s)} \quad (9)$$

This result shows that the limitation on the maximum sensitivity is determined by the larger of the quantities KL and $\delta\varphi_2$. We note that in Eq. (9), the sensitivity changes sign when $KL \sim \delta\varphi_2$. This corresponds to a transition between the slow light and fast light regions [13, 19]. Because

KL is always positive, the situation when φ_2 is exactly equal to π corresponds to the slow-light configuration.

As noted previously [15], there exist two sensing windows, spaced symmetrically around the Stokes frequency. Within each sensing window, and provided that KL is small, the phase shift θ_1 varies monotonically with $\delta\omega_s$ between either zero and π , for the slow-light configuration, or between zero and $-\pi$ for the fast-light configuration. At the position of maximum sensitivity, which occurs in the middle of the sensing window, θ_1 is equal to $\pm\pi/2$.

Fig. 2. Calculated amplitude of the first order harmonic wave i_1 (black solid line) and the amplitude of the second order harmonic wave i_2 (black dotted line) at different sensitivity with $\hat{G}_0 = 2$ and $\varphi_2 = \pi$. The blue dash curve shows the sensitivity S .

From the above analysis, we note that Eq. (7) for the modulation phase shift was derived assuming only the first-order harmonic. However, the actual output Stokes wave (see Eq. (3) and Eq. (5)) contains higher-order harmonics. Figure 2 shows the theoretically calculated amplitudes of first- and second-order harmonics around the sensing window (centered around 17 MHz) as calculated using Eq. (10) and Eq. (14) from [14], for a 7 cm chalcogenide rib-waveguide used in the experiments. For these calculations we used the following parameters: $n = 2.4$, $\Gamma_B = 34$ MHz, $f_{mod} = 50$ kHz, $\hat{G}_0 = \alpha G_0 / \beta = 2$ and $\varphi_2 = \pi$. From Fig. 2, we note that the amplitude of the second-order harmonic is larger than that of the fundamental in the sensing window where the spectral sensitivity S is large. Therefore, in order to measure the phase change of first harmonic wave, higher-order harmonics must be removed in the experiment. In our experiments, we used an electrical filter to remove the higher harmonics.

The calculations shown in Fig. 2 were performed for a sensing window centered around 17 MHz. However, the position of the sensing window, defined by the detuning of its center frequency from the peak of the Brillouin resonance, varies with the value of $\hat{G}_0$ [15]. In Fig. 3 we show the calculated position of the sensing window and the corresponding maximum sensitivity S for different values of $\hat{G}_0$. Typically the sensing window is a narrow frequency region around the center frequency. However, it is possible to apply the sensing technique in a large frequency range around the the peak of the Brillouin resonance by changing the value of $\hat{G}_0$. From Fig. 3, we note that when $\hat{G}_0$ increased from 1.5 to 5.5, the maximum sensitivity varies slowly, changing less than 25%.

Fig. 3. Calculated maximum sensitivity (black solid line) and position of the sensing window (blue dotted line) with different G_0 .

Fig. 4. The configuration of the experiment. FG1 and FG2 are function generators; FPC1-4 is the fiber polarization controller; SG is the signal generator to create Stokes wave; C1, C2 and C3 are circulators; EOML1, EOML2 and EOMH are intensity modulators; EDFA is the Erbium doped fiber amplifier; OSA is the optical spectrum analyzer; D is optical detector; BPF is electronic band pass filter and OS is the oscilloscope. Blue wires indicate the electronic wire.

3. Experiment

Figure 4 shows the experimental set-up for the on-chip Brillouin MMXGM sensor. A tunable laser around 1550 nm was split with a 50/50 coupler to generate the pump and Stokes wave. After the Stokes signal was generated in one arm using the intensity modulator EOMH (electro-optic modulator of high frequency) driven by a signal generator SG, the light in both the arms was sinusoidally modulated by intensity modulators EOML1 and EOML2 (electro-optic modulator of low frequency) driven by function generators FG1 and FG2 at 50 kHz. The modulation phase could be controlled by adjusting the phase delay from the function generator FG2 triggered by FG1. Both the pump and signal were amplified by erbium doped fiber amplifiers (EDFAs) and coupled to a 7 cm long waveguide with a cross section $4\mu\text{m}\times 850\text{nm}$ through circulators (C1, C2) using lensed fibers. The total insertion loss was around 13 dB during the experiment, measured through port 3 of C1. The amplified Stokes signal was sent into a circulator C3 with a Bragg grating connected to port 2 (see Fig. 4). The 3dB-bandwidth of the Bragg grating was about 0.13 nm and one of its steep edges of the reflection peak was used to suppress the parasitic pump originated from the reflection at the chip input facet. The filtered signal was split using a 99/1 coupler where the 1% port was sent to the OSA and the 99% port was sent to a photo detector D. An electronic band pass filter BPF with a 2 kHz bandwidth was used before the detector to filter out the higher harmonics and DC component. The electronically filtered signal was observed on the oscilloscope OS.

From Fig. 3, we note that the frequency at which the maximum sensitivity occurs depends on the value of $\hat{G}_0$, which enables the application of this technique over a large frequency range around the peak of the Brillouin resonance (~ 7.63 GHz). In our experiment, we first adjusted the pump and Stokes polarization to achieve a maximum gain ($\sim 5\text{-}6$ dB) at the peak of the Brillouin gain while keeping $\alpha \approx \beta \approx 0$. In order to show that we can achieve large sensitivity for any frequency around the peak of the Brillouin resonance by adjusting the value of $\hat{G}_0$, we arbitrarily picked a frequency detuning of $\Delta(\delta\omega_s) \sim 25$ MHz up-shifted from the peak of the Brillouin resonance. By observing the pump and Stokes waveform on OS, at port 2 of C1, we set $\varphi_2 = \pi$. The value of $\hat{G}_0$ was then varied by adjusting the modulation depths α and β (whilst keeping them small) so that $\theta_1 = \pi/2$, which corresponds to the maximum sensitivity, occurs at $\Delta(\delta\omega_s) \sim 25$ MHz. Finally, we measured the sensitivity for a range of different values of φ_2 around a detuning $\delta\omega_s \sim 25$ MHz, and determined the value of φ_2 for which the sensitivity was maximized. With this optimized value of φ_2 , the frequency of the Stokes was detuned from $\delta\omega_s \sim 25$ MHz in steps of 100 kHz to observe the phase shift evolution of the first-harmonic on OS. In our experiments, the maximum sensitivity was obtained for a phase evolution from $-\pi$ to 0, therefore occurring in the fast-light regime. We also observed phase evolution from the slow-light regime of 0 to π , however the sensitivity at this value of φ_2 was smaller. In the following we present here the results for the overall maximum sensitivity from the fast-light regime.

Figure 5 shows the output waveform recorded on OS with the largest sensitivity we could obtain at the modulation frequency of 50 kHz, together with the normalized phase shift of the first harmonic wave. The black dashed curve in the center of Fig. 5(A) shows the evolution of the phase when the frequency detuning was changed. A phase shift evolution from $-\pi$ to 0 was observed when the frequency was detuned from 24.876 MHz to 25.876 MHz in steps of 100 kHz. In our experiment, we observed a small distortion arising from the residual higher-order harmonics remaining after the band pass filter. The normalized phase shift plotted in Fig. 5 (B) shows a phase shift from $-\pi$ to 0 when the frequency was detuned away from the peak of the Brillouin resonance. A maximum phase shift of $\Delta\theta_1 \sim 0.95$ rad was observed around detuning of 25.476 MHz (see Fig. 5(B)), corresponding to a maximum sensitivity of ~ 9.5 mrad/kHz. The maximum attainable sensitivity is limited by the ability to measure the phase change of

Fig. 5. The output first harmonic wave measured at different frequency detunings and the normalized phase shift of the first harmonic wave together with the simulation. The black dash curve in (A) shows the evolution of the modulation phase when the frequency of signal is detuning. The normalized phase shift is shown in (B). The red solid curve is the calculation with $\hat{G}_0=3.245$ and $\varphi_2=1.0009\pi$ and the sensing window is around 450 kHz.

the first harmonic, the amplitude of which approaches zero near the maximum sensitivity point. The frequency window of large sensitivity is ~ 450 kHz, within which the normalized phase shift changed from 0.9 to 0.1. By fitting the experimental result to the theoretical phase shift given by Eq. (7), which is presented as the red solid curve in Fig. 5(B), we deduce values of $\hat{G}_0=3.245$ and $\varphi_2=1.0009\pi$, thereby confirming that the sensing window lies in the fast-light region.

4. Conclusion

In conclusion, we have demonstrated a high spectral sensitivity on-chip Brillouin MMXGM frequency sensor. A spectral sensitivity of ~ 9.5 mrad/kHz was achieved for a 50 kHz modulation in the fast-light regime, which is of comparable sensitivity to km-long fiber experiments. This demonstration paves the way for photonic integration of high sensitivity spectral sensors.

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