

Backscatter-immune, polarization managed, all fiber Sagnac sensing interferometer

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Abstract: We propose a new all fiber Mach-Zehnder-Sagnac hybrid interferometer topology for precision sensing. This configuration utilizes a high coherence laser source, mitigates the effects of Rayleigh backscatter and polarization wander, while eliminating scale factor drift. We also present preliminary experimental results, using telecommunications grade single mode fiber and fiber couplers, to demonstrate its principle of operation.

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1. Introduction

Sagnac interferometers have found use in a range of sensing applications. Due to the inherent common optical path, the interferometer automatically operates at a fringe, regardless of both

optical frequency and tuning within the interferometer. This ensures the common mode rejection of many otherwise debilitating noise sources, such as mechanical perturbations, yielding a high signal to noise ratio for the desired quantity.

While the dominant use of Sagnac interferometers is in fiber optic gyroscopes [1] for the measurement of mechanical rotation, a number of other applications have emerged. These include non-linear spectroscopy [2, 3], sensing electrical current via the Verdet constant of glass fibers [4], as well as the interferometric detection of gravitational waves [5, 6].

It is well known that the sensitivity of an ideal Sagnac gyroscope improves with its optical interferometer path length. One of the main limiting factors encountered in long-length fiber Sagnac interferometers is similar to those encountered in fiber remote sensing: random phase noise associated with Rayleigh backscatter.

Another important issue relates to polarization wander within the Sagnac coil, causing phase detuning which cannot be distinguished from a real rotation signal. This debilitating noise source is usually removed by adopting the minimum configuration for reciprocal gyroscopes [1].

In this letter we propose a new, all fiber Mach-Zehnder-Sagnac interferometer (MZ-SI) hybrid sensing topology with radio-frequency (RF) laser locking. This is distinct from previous examples of Mach-Zehnder-Sagnac configurations, where hybrids were used for distributed location sensing of large signals [7, 8]. In high resolution sensing of non-reciprocal phase change, on the other hand, where application areas include mechanical rotation sensing, electrical current sensing and distributed perimeter sensing, our technique offers potential advantages in a number of areas. These include (a) elimination of Rayleigh backscatter; (b) mitigation of phase detuning effects due to polarization wander; and (c) stabilization of scale factor [1] drift. Our solution is simple and potentially cost-effective, requiring only a diode laser, several fiber couplers and single mode fiber. We will also present some preliminary experimental data in support of the principle of operation.

2. The Mach-Zehnder-Sagnac Interferometer: Principle of Operation

2.1. The Mach-Zehnder Interferometer

Figure 1(a) shows a fiber based realization of a Mach-Zehnder Interferometer (MZI) where the lower arm has been extended by ΔL to yield a mismatched arm length interferometer. The MZI has two 50/50, or 3 dB, 2x2 couplers, where the input coupler is coupler I, while the output coupler is coupler II. Each coupler has 4 ports: a, b, c and d, as labelled in Fig. 1(a). The laser is phase modulated at radio-frequencies (RF), such that the laser carrier and its modulation sidebands have optical frequencies ν , and $\nu \pm \nu_{mod}$ respectively.

The reference arm has optical path length (OPL) L while the lower test arm has an OPL of $L + \Delta L$. The frequency response of this MZI is straight forward to analyze [9]:

$$\mathbf{E}_{Ia-IIc} = e^{-j\omega L/c} (t_{Iac}t_{IIac} - t_{Iad}t_{IIbc}e^{j\omega\Delta L/c}), \quad (1)$$

$$\mathbf{E}_{Ia-II d} = e^{-j\omega L/c} (jt_{Iac}t_{IIad} - jt_{Iad}t_{IIbd}e^{j\omega\Delta L/c}), \quad (2)$$

$$\mathbf{E}_{Ib-IIc} = e^{-j\omega L/c} (jt_{Ibc}t_{IIac} + jt_{Ibd}t_{IIbc}e^{j\omega\Delta L/c}), \quad (3)$$

$$\mathbf{E}_{Ib-II d} = e^{-j\omega L/c} (-t_{Ibc}t_{IIad} + t_{Ibd}t_{IIbd}e^{j\omega\Delta L/c}), \quad (4)$$

where $\omega = 2\pi\nu$ is the optical frequency in units of rad/s. The amplitude transmissions, t , between two ports for each coupler can be identified by their subscripts in Eqs. (1-4). For example, the amplitude transmission from port a to port c of Coupler I is t_{Iac} , while that from port b to port c of coupler II is t_{IIbc} . Similarly, the frequency response, $\mathbf{E}$ between two ports in the MZI can be identified by their subscripts, such that $\mathbf{E}_{Ia-IIc}$ denotes the frequency response from port

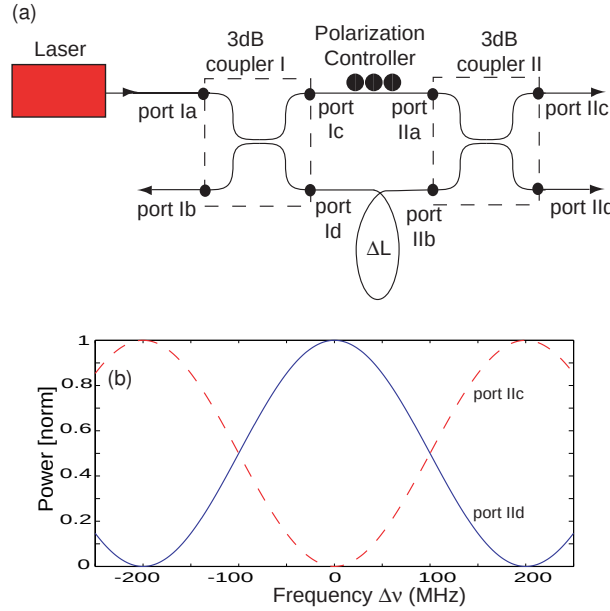


Fig. 1. (a). Schematic of a Mach-Zehnder Interferometer with a delay of ΔL in one arm; b) frequency response of the MZI with $\Delta L = 0.75\text{m}$

Ia to port IIc. For Eqs. (1 to 2), we have adopted the convention that transmission from port a to d, and port b to c each pick up a phase shift of $\pi/2$.

Due to the reciprocal nature of all components within the MZI, the reverse response is identical to the forward response, such that

$$\mathbf{E}_{\text{Ia-IIc}} = \mathbf{E}_{\text{IIc-Ia}} \quad (5)$$

$$\mathbf{E}_{\text{Ia-IId}} = \mathbf{E}_{\text{IIId-Ia}} \quad (6)$$

$$\mathbf{E}_{\text{Ib-IIc}} = \mathbf{E}_{\text{IIc-Ib}} \quad (7)$$

$$\mathbf{E}_{\text{Ib-IIId}} = \mathbf{E}_{\text{IIId-Ib}} \quad (8)$$

ΔL causes the fringe condition of the MZI outputs to become a function of frequency. From Eqs. (1 to 4), it can be seen that the fringe frequency spacing is inversely proportional to the arm OPL mismatch ΔL . Figure 1(b) plots the output power distribution at ports IIc and IId as a function of laser frequency incident on port Ia. It is assumed that both 2x2 couplers are lossless and have a coupling ratio of 50/50, while $\Delta L = 0.75\text{ m}$ of OPL. The polarization controller in the upper short arm of the MZI ensures that the polarization states of the two arms are matched upon recombination by 3dB coupler II, and we assume this facilitates a fringe visibility of ~ 1 . If the laser was modulated at 200 MHz, or half the free-spectral-range (FSR) of the MZI, it can be seen from Fig. 1(b) that when the laser carrier field exits the MZI entirely at port IId, its modulation sidebands at $\pm 200\text{ MHz}$ on either side of the carrier exit entirely at port IIc.

2.2. The Mach-Zehnder and Sagnac Interferometer tandem

Figure 2 presents a schematic of the complete sensing interferometer configuration proposed. A single frequency laser is frequency tuned to correspond to 0 Hz in Fig. 1(b). The laser is then phase modulated to add RF sidebands to the laser spectrum, where the modulation frequency

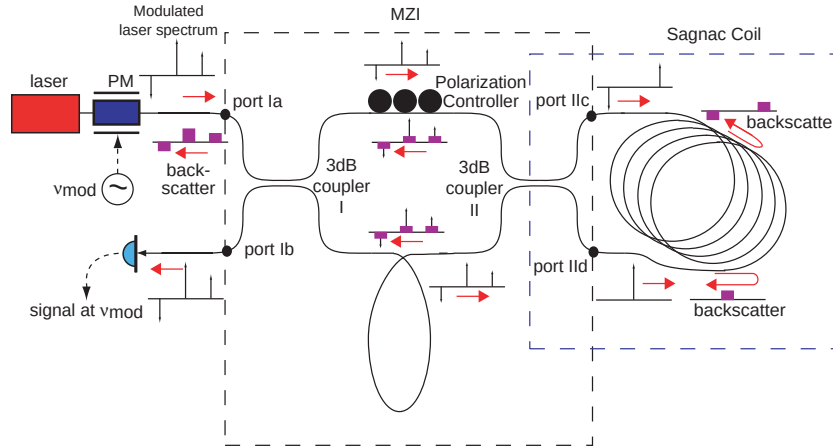


Fig. 2. Schematic of the full Sagnac system, including the Mach-Zehnder Interferometer with a delay of δL in one arm. Representations of the expected frequency spectra for the laser carrier, its RF sidebands, and backscattered components, together with their propagation direction, are included at various stages of the hybrid interferometer as they traverse the system.

equals half the FSR of the MZI, such that

$$\nu_{mod} = \frac{c}{2\Delta L}, \quad (9)$$

where c is the speed of light. In the forward pass of the MZI, the modulated laser is coupled into the system via 3dB coupler I of the MZI. This coupler simply splits all spectral components into the two arms of the MZI.

If the MZI fringe visibility is ~ 1 , then the arm length mismatch, and hence its frequency dependent response demultiplexes the carrier from its RF sidebands to port IId and IIc respectively upon recombination after Coupler II, according to Fig. 1(b).

After travelling through the Sagnac coil in the same direction, the two sidebands then re-enter the MZI at port IId. Both the upper and lower sidebands then traverse the MZI in the reverse pass to emerge at port Ib, as governed by Eq. (8).

The carrier, on the other hand, emerges at port IId on the forward pass of the MZI, and traverses the Sagnac coil in the opposite direction to the sidebands, before re-entering the MZI at port IIc for the reverse pass. This ensures that the carrier also exits the MZI at port Ib. Representations of the expected frequency spectra for the laser carrier, its RF sidebands, together with their propagation directions, are illustrated in Fig. 2 at various stages of the hybrid interferometer as they traverse the system. Fig. 3 shows the total transfer function from port Ia, through the MZI, around the Sagnac coil, back through the MZI and out to ports Ia and Ib.

At port Ib, the upper and lower sidebands beat with the carrier to yield a RF beat at the modulation frequency. The phase of this RF signal reproduces the relative phase difference between the sidebands, which travel clockwise within the Sagnac coil, and the carrier, which travels anticlockwise in the Sagnac coil. This phase readout can therefore be used for Sagnac signal extraction.

2.3. Interferometer active locking

Figure 4 shows the experimental interferometer schematic including both signal extraction and locking details. As the MZI is operated at a turning point for both the carrier and sidebands, it is

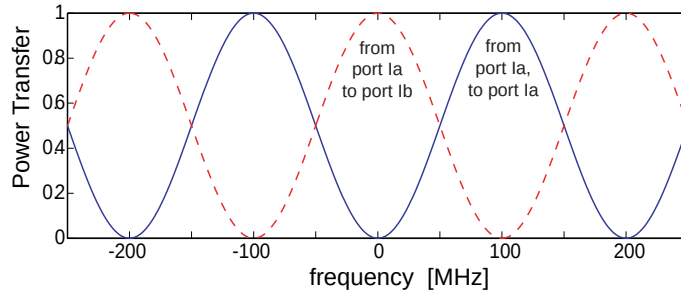


Fig. 3. Complete optical power transfer, as a function of optical frequency, from input at port Ia, through the system and back to ports Ia and Ib.

necessary to add an additional low frequency modulation in order to dither the laser frequency components around their respective MZI turning points. This dither can then be demodulated directly to yield an error signal that is fed back to the laser. The feedback locks the laser to the desired operating point, maximizing the laser carrier output power from the MZI at port II_d, and the sideband output power from the MZI at port II_c, thus optimizing interferometer sensitivity.

Actively locking the laser frequency to an MZI fringe stabilizes the laser wavelength relative to the MZI arm length mismatch ΔL . This, in turn, minimizes scale factor drift at the Sagnac signal readout. In addition, as the MZI arm length mismatch is physically composed of single mode fiber, identical to that of the Sagnac sensing coil, temperature drifts common to both will be tracked by the laser servo. This will produce a self compensating scale factor that is immune to temperature drift to first order.

2.4. Signal extraction

A complete schematic of the proposed interferometer is shown in Fig. 4. The signal is extracted at port Ib using a RF phase meter that is synchronized to the modulation frequency. The phase meter output then yields the differential phase of the Sagnac:

$$\phi_{\text{phase meter}} = \phi_{\text{cw}} - \phi_{\text{ccw}}, \quad (10)$$

where $\phi_{\text{phase meter}}$ signifies the phase readout by the phase meter, while ϕ_{cw} and ϕ_{ccw} are the optical phase of light at coupler II after traveling in the clockwise and counterclockwise directions in the Sagnac coil.

3. Backscatter rejection

As the upper and lower sidebands exit the MZI at port II_c on their forward transit, any backscatter events (including RBS and parasitic back-reflections) would travel counter-clockwise in the Sagnac coil. These backscattered sidebands re-enter the MZI for the reverse transit via port II_c, and traverse back through the MZI to emerge at port Ia alone. Similarly, backscatter of the carrier within the Sagnac coil travels clockwise to re-enter the MZI via port II_d, and is returned to port Ia only. The backscattered components in the Sagnac coil at various stages of the hybrid interferometer, together with their propagation directions, are illustrated in Fig. 2.

Figure 5 plots the normalized backscatter power emerging at ports Ia and Ib. As can be seen, backscatter at both the upper and lower sideband frequencies, as well as the carrier field is directed back to port Ia and dumped. The signal output recovered at port Ib is therefore free of backscatter, independent of the coherence length of the laser source used.

Hence, the MZI acts as a discriminator between forward travelling laser light and unwanted backscattering events in the Sagnac coil for all spectral components of the modulated laser. The

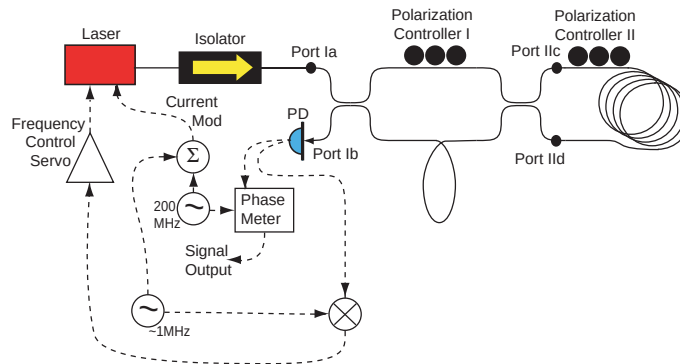


Fig. 4. The interferometer schematic showing both signal extraction and locking electronics.

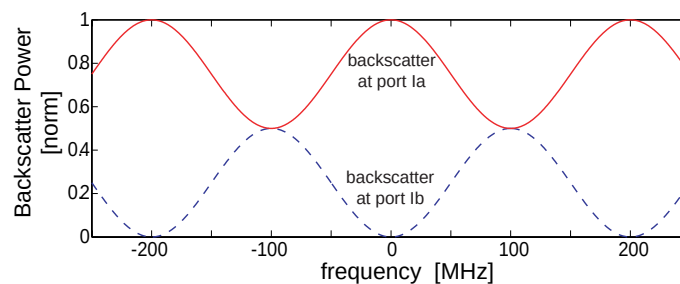


Fig. 5. Backscatter distribution at ports Ia and Ib as a function of optical frequency.

MZI and Sagnac coil act as a powerful tandem to demultiplex useful laser light from unwanted backscatter.

4. Polarization management

Fiber couplers, such as the 3dB couplers used here, exhibit a polarization sensitive phase shift [10]. This implies that polarization wander within the Sagnac coil will cause phase detuning of the Sagnac and mimic a real rotation signal. This source of noise is debilitating if left unchecked. The standard approach to overcome polarization wander induced noise is to introduce a polarization element that both polarizes the outgoing light source and also polarizes the light after transiting through the Sagnac coil on its way to the signal photodetector. In our configuration however, the implementation of such a solution is complicated by the need to place the polarization element within the MZI such that both arms of the MZI are polarized with their respective polarization axes accurately matched.

On close inspection of the operation of the MZI, it becomes apparent that the MZI inherently functions as the desired polarization element when the laser is locked to the correct operating point (turning point of the MZI for both the carrier and upper and lower sidebands) and the MZI fringe visibility approaches unity. Under these conditions, the polarization evolution within one arm of the MZI is matched to the other arm by use of a polarization controller such that the two arms interfere with high efficiency at the second 3dB coupler. Return light of the same polarization is processed as expected and transmitted to the signal photodetector output (port 1b) to produce a valid signal. Light that has become cross polarized during its transit through the Sagnac coil however will now experience a MZI that is 180 degrees offset compared to the

correctly polarized light. This phase shift, inherent in the polarization transformations occurring within the MZI arms, ensures that all cross polarized light will return to the laser (port 1a) and does not produce an output at the signal port 1b. Thus when locked, the MZI acts as a polarizing element for the signal output port 1b. This ensures that our configuration is a reciprocal optical network and should enable precision Sagnac measurements.

This polarizing behavior of the MZI can be analyzed using Jones matrices in a straight forward manner. After linearly polarized laser light is coupled into Coupler I, it is split into the two MZI arms. For short lengths of SMF-28 fiber in one MZI arm, it is reasonable to assume that birefringence is negligible, and the only polarization effect on linearly polarized light is an indeterminate angle of pure rotation. This rotation can be matched in the other MZI arm with a polarization controller before the two arms are recombined by Coupler II (see Fig. 2). The Jones transformation matrices for the two arms can be written as [11]:

$$\mathbf{T}_{\text{pc}} = \begin{pmatrix} 2 \sin \theta_{hw} \cos \theta_{hw} & \sin^2 \theta_{hw} - \cos^2 \theta_{hw} \\ \sin^2 \theta_{hw} - \cos^2 \theta_{hw} & -2 \sin \theta_{hw} \cos \theta_{hw} \end{pmatrix} \quad (11)$$

$$\mathbf{T}_{\text{delay}} = \begin{pmatrix} \cos \theta_{rot.} & -\sin \theta_{rot.} \\ \sin \theta_{rot.} & \cos \theta_{rot.} \end{pmatrix} \quad (12)$$

where $\mathbf{T}_{\text{pc}}$ relates to the polarization controller acting as a half-wave plate, with a fast axis angle of θ_{hw} relative to the laboratory frame, while $\mathbf{T}_{\text{delay}}$ in the longer MZI delay arm simply rotates the linearly polarized light by an angle $\theta_{rot.}$ relative to the laboratory frame.

Let us suppose that the input laser light $\mathbf{I}_{in}$ is linearly polarized, such that:

$$\mathbf{I}_{in} = \begin{pmatrix} \cos \theta_{in} \\ \sin \theta_{in} \end{pmatrix} \quad (13)$$

where θ_{in} is the angle of polarization in the laboratory frame.

The polarization states of the light in each MZI arm just before recombination can then be written as:

$$\mathbf{I}_{\text{pc}} = \mathbf{T}_{\text{pc}} \mathbf{I}_{in} \quad (14)$$

$$\mathbf{I}_{\text{delay}} = \mathbf{T}_{\text{delay}} \mathbf{I}_{in} \quad (15)$$

and easily derived to be:

$$\mathbf{I}_{\text{pc}} = \begin{pmatrix} \sin[2\theta_{hw} - \theta_{in}] \\ -\cos[2\theta_{hw} - \theta_{in}] \end{pmatrix} \quad (16)$$

$$\mathbf{I}_{\text{delay}} = \begin{pmatrix} \cos[\theta_{rot.} + \theta_{in}] \\ \sin[\theta_{rot.} + \theta_{in}] \end{pmatrix} \quad (17)$$

where $\mathbf{I}_{\text{pc}}$ is the polarization state of the polarization controlled arm, while $\mathbf{I}_{\text{delay}}$ is that of the delay arm, both just before recombination by a 3dB coupler.

If the polarization controller was adjusted such that the polarization states in the two arms are matched before being recombined by Coupler II, then $\mathbf{I}_{\text{pc}} \equiv \mathbf{I}_{\text{delay}}$, yielding a simple relationship between θ_{hw} and $\theta_{rot.}$:

$$\theta_{rot.} = 2\theta_{hw} - 2\theta_{in} - \frac{\pi}{2}. \quad (18)$$

Equation (18) describes the the desired operating condition for the polarization controller, where it acts as a half-wave plate with a fast axis angle of θ_{hw} with respect to the laboratory

frame. Under this operating condition, the MZI yields maximum fringe visibility for the given θ_{in} and $\theta_{rot.}$.

It is instructive to then analyze the response of the MZI, under this same operating condition, for any orthogonally polarized input light, such that:

$$\mathbf{I}_{in} = \begin{pmatrix} \cos[\theta_{in} + \frac{\pi}{2}] \\ \sin[\theta_{in} + \frac{\pi}{2}] \end{pmatrix}. \quad (19)$$

The polarization states in each arm just before recombination can be derived, according to Eqs. (14) and (15), after substituting Eq. (18) into Eq. (12), and shown to be:

$$\mathbf{I}_{pc} = \begin{pmatrix} -\cos[2\theta_{hw} - \theta_{in}] \\ -\sin[2\theta_{hw} - \theta_{in}] \end{pmatrix} \quad (20)$$

$$\mathbf{I}_{delay} = \begin{pmatrix} \cos[2\theta_{hw} - \theta_{in}] \\ \sin[2\theta_{hw} - \theta_{in}] \end{pmatrix}. \quad (21)$$

The negative coefficients in the Jones vector of Eq. (20) imply that this cross polarized term picks up an additional π phase in the shorter arm. Thus the MZI fringe is translated by $FSR/2$ for orthogonally polarized field components. This is an important realization, because when the laser is locked to the MZI mismatch, such that the carrier power exits at port IId in the forward direction, any orthogonal polarization component is dumped into port IIc together with the sidebands. This light is orthogonal in polarization to the RF sidebands. Hence, as they traverse the Sagnac coil, and then re-enter the MZI via port IId in reverse, the MZI again acts as a polarization demultiplexer by directing the sidebands to port Ib, and separating the orthogonal polarization to be dumped at port Ia. The treatment for any RF sidebands with unwanted polarization components is the same. They traverse the Sagnac Coil with the main laser carrier in the counterclockwise direction, but are eventually dumped at port Ia in the reverse direction. Likewise, cross polarization components occurring within the Sagnac coil exit at port Ia and are dumped. The field components measured at port Ib are therefore polarization filtered to remove cross polarized components.

If the MZI is constructed such that both the 3dB couplers and the arms of the MZI are made of PM fiber, then the operation of one polarization is decoupled with respect to the other and the MZI no longer functions as an implicit polarizing element. However, by using a polarization controller within one arm of the MZI, the relative fringe position of one polarization can be tuned with respect to the orthogonal polarization. Hence, an intentional phase offset of 180 degrees can be implemented within the MZI such that the PM MZI acts as a polarizer and rejects the undesired polarization from the signal port 1B when the laser is locked at the correct position.

5. Preliminary experimental demonstration of the Mach-Zehnder-Sagnac Interferometer

5.1. Experimental technique

In this section, we present some preliminary experimental results to demonstrate the principle of operation of the MZ-SI. A table-top experiment as illustrated by Fig. 4, using all SMF-28 telecommunications fiber was constructed. The light source was a New Focus Vortex external cavity diode laser at 1550 nm, and was directly current modulated with a signal generator. The optical isolator was used to isolate the laser from the unwanted light dumped at Port Ia. The length mismatch in the MZI was ~ 0.65 m, while the total Sagnac coil length was ~ 5 km. A polarization controller was used in the short arm of the MZI to optimize its fringe visibility to better than 0.99. This MZI fringe visibility did not deteriorate over several hours under typical

laboratory conditions. The second polarization controller in the Sagnac coil is used to ensure that the total polarization transformation in the coil is unity. Experimentally the Sagnac coil polarization controller was set up to maximize the signal power at port Ib.

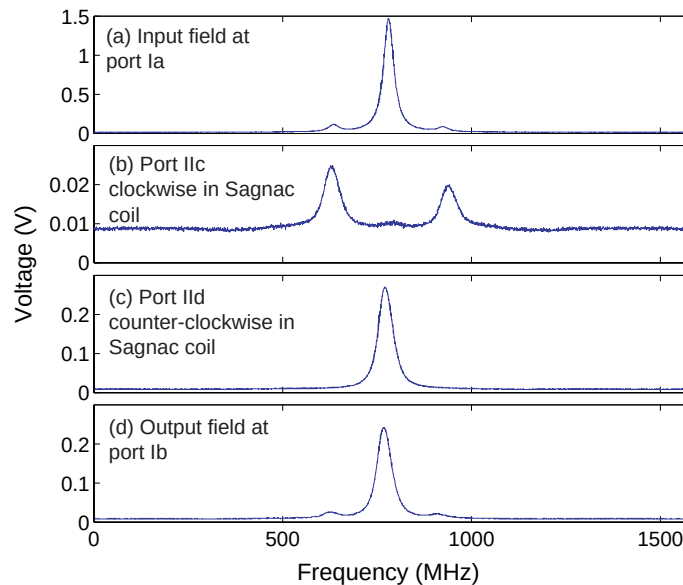


Fig. 6. Plots showing experimental spectral scans of carrier and sidebands at various points of transit in the Mach-Zehnder-Sagnac Interferometer.

The frequency of the laser was dithered at 100 kHz and locked to the MZI fringe turning point using a lock-in amplifier, as described by Section 2.4. The RF modulation frequency was then tuned and optimized by monitoring the optical output at the MZI ports IIc and IId, in the forward direction. These outputs were analyzed using an optical spectrum analyzer (OSA), which was made up of a confocal free-space scanning Fabry-Perot cavity. When the carrier and its RF sidebands are completely demultiplexed as detailed in Section 2.2, we knew that the RF modulation frequency was precisely tuned to half the free-spectral-range of the MZI. This optimized modulation frequency was found to be 155 MHz.

A small section of the Sagnac coil was mounted on a PZT stretcher, so that a calibrated signal could be introduced to the system.

5.2. Experimental results

Figure 6 illustrate the spectral components traversing the MZ-SI at various points of transit. The input laser carrier and its RF current modulated sidebands are observed using the OSA, and illustrated in Fig. 6(a). This modulated laser light is injected into the MZ-SI via port Ia.

The demultiplexed RF sidebands, spaced 310 MHz apart, are observed at port IIc, and displayed in Fig. 6(b), showing that most of the carrier power did not emerge at this port. The asymmetry in the sidebands is due to the nature of diode current modulation. While current modulation introduces primarily frequency modulation to the laser, a small amount of amplitude modulation is present at the same time [12]. This results in unequal amplitudes in the sidebands.

Most of the laser carrier power emerges at port IId, as displayed in Fig. 6(c), where the RF sidebands are visibly absent in the OSA spectrum. Finally, in the reverse pass, the laser carrier and RF sidebands are multiplexed by the MZI and exit the system at port Ib. This recombined

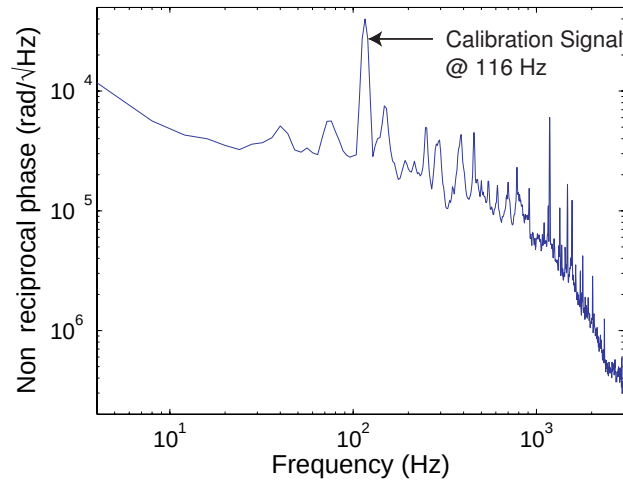


Fig. 7. The noise power spectral density of the Mach-Zehnder-Sagnac Interferometer system. A calibrated non-reciprocal phase signal of $400 \mu\text{rad}/\sqrt{\text{Hz}}$ at 116 Hz was introduced in the Sagnac coil.

OSA spectrum is shown in Fig. 6(d).

A Stanford Research Lock-in Amplifier was used as a phase meter, and the output from port Ib was received by a RF photodetector, whereupon the electrical signal was measured with the Lock-in Amplifier to extract the non-reciprocal phase. A small calibrated signal of $400 \mu\text{rad}/\sqrt{\text{Hz}}$ at 116 Hz was injected in the Sagnac coil. The calibrated noise power spectrum of the MZ-SI system is displayed in Fig. 7, where the peak at 116 Hz is the calibrated signal introduced by a PZT stretcher.

The evident roll-off in the power spectrum in Fig. 7, with a corner frequency of 1.6 kHz, is caused by low pass filtering within the Lock-in Amplifier.

6. Conclusion

In this paper we have proposed a novel Mach-Zehnder-Sagnac interferometer configuration for the precise measurement of non-reciprocal optical signals. One advantage of this configuration is the removal of backscatter noise from the measurement, thus enabling the use of a high coherence single frequency source. When this single-frequency laser is locked to the MZI arm length difference, it stabilizes the scale factor of the Sagnac measurement. Furthermore, when the light source is locked, the MZI functions as a polarizer for both the source upon entering the Sagnac coil and for the return light leaving the Sagnac coil for the photodetector. This ensures that the complete Mach-Zehnder-Sagnac interferometer is a reciprocal optical network enabling sensitive long term measurements. While we have not addressed the issue of phase bias and phase bias drift in this paper, we believe this issue can be readily accommodated with minimal increase in system complexity. Finally, this interferometer can be readily manufactured from all fiber components, enabling a high performance, low cost measurement system.