Michelson Interferometer With Faraday Mirrors Employed In A Delayed Self-Heterodyne Interferometer

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Abstract: Faraday rotator mirrors in a Michelson interferometer configuration is shown to significantly improve resolution and coherence for delayed self-heterodyne interferometery. Coherence is clearly observed over the maximum available delay length of 60 km.

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1. Introduction

The bandwidth of high coherence sources, such as ultra-narrow linewidth lasers [1], are commonly estimated with the delayed self-heterodyne interferometry (DSHI) method [2].The standard Mach-Zender interferometer (MZI) experimental arrangement for DSHI works by splitting the signal from the device-under-test (DUT) using a fibre coupler into two separate paths. One path passes through an acousto-optic modulator (AOM) that serves to frequency- (wavelength-) shift the incident light by approximately 25-50 MHz whilst the other path experiences a temporal delay due to an additional optical delay length of the fibre. When the signals recombine at the output, the interference is detected by a fast photodiode (PD). A beat signal arising from the laser frequency and the AOM shifted frequency can be viewed on a radio frequency spectrum analyser (RFSA) centred at the frequency shift. The beat spectrum represents a convolution of the two signals in frequency space.

When the delay-time, τ_d, through the fibre is much greater than the coherence time, τ, of the laser, the merged signals can be considered as totally uncorrelated, i.e. there is no coherent mixing. The resultant RFSA beat spectrum S(f) as a function of I(τ), the temporal intensity, may be expressed as:

$$S(f) = \Im[e^{\{-8I(\tau)\}}]; \qquad I(\tau) = \int_0^\infty S_F(\nu)\frac{\sin^2 \pi\nu\tau}{\nu^2}\sin^2(\pi\nu\tau_d)d\nu \qquad (1)$$

$S_f(\nu)$ is the frequency noise spectrum, ν is the frequency variable, τ is the coherence time of the DUT, and τ_d is the delay time [3]. In semiconductor lasers, the noise is usually white, (often closer to a 1/f characteristic dependence), leading to a purely Lorentzian shape of the beat signal in frequency space; the linewidth of the laser may then be extracted as being half of the full width half maximum (FWHM) of the Lorentzian profile. For DFB fibre lasers, however, the dominant contribution to noise is frequency dependant phonon mediated relaxation processes that are mainly found in the low kHz frequency domain, which result in a Gaussian shape of the RFSA beat spectrum [3]. Noise broadens the laser linewidth spectrum, which when combined with fibre dispersive effects dominate the measured spectrum when long fibre delay lines are necessary.

For ultra-narrow linewidth sources, $\tau_d > \tau$ are often impracticable since fibre noise and dispersion lead to unacceptable degradation of the measured linewidth. In these cases, sub-coherence length delay-coils are used, requiring a modified analysis. In the extreme sub-coherence case, where the lengths of both arms are equal, the interfering light will generate a sharp peak in the observed RFSA beat spectrum, nominally a delta, δ, function. In practice, however, the δ function is broadened by several noise contributions from instruments and the fibre itself. As the delay time, τ_d, is increased, the beat spectrum transforms from a sharp quasi δ-peak to a Lorentzian (or more realistically for a fibre laser to a convoluted Lorentzian-Gaussian shape) with side-lobes indicating coherent mixing of the two signals. Building on previous work [4], Han et. al. [5] proposed that the power spectral density of the DSHI signal for Lorentzian (semiconductor) sources in the sub-coherence domain could be represented analytically by (2):

$$S(\omega,\tau) = \frac{2\Delta\omega}{\Delta\omega^2+\omega^2}\left\{1-e^{-\Delta\omega\tau}\left[\cos\Delta\omega\tau+\frac{\Delta\omega}{\omega}\sin\Delta\omega\tau\right]\right\}+e^{-\Delta\omega\tau}\delta(\omega) \qquad (2)$$

where, τ is the delay time and ω is defined as the angular frequency deviated from the AOM carrier frequency.

In this work, we explore and compare a Michelson interferometer (MI) configuration using fibre coupled Faraday rotator mirrors (FRM) against a Mach Zehnder interferometer (MZI) for DSHI [6]. The main potential advantages with MI include: (1) a doubling of the path-length due to double delay-line pass geometry, (2) reduced gyroscopic effects [potentially originating from rotational vibrations in the delay coil] due to a counter-propagating double-pass and (3) reduced polarisation fringe fading. (The Faraday rotator mirrors act as phase conjugate mirrors, creating a phase delay of 90 degrees so that most of the induced birefringence the beam experiences during the first leg of the delay-line is undone on the return leg, thus minimising any mixing of the signals of orthogonal polarisations).

2. Experiments and modelling

The two DSHI configurations were tested using a single-mode stable narrow-band ring-DFB fibre laser [1] as a signal source, shown schematically in Fig. 1.

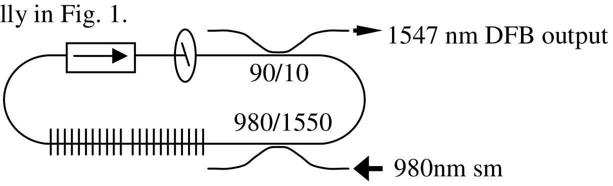

Figure 1. Signal-source, narrow-band ring-DFB fibre laser configuration.

The output from the Er-doped DFB fibre laser was fed through an optical isolator and a polarizer to ensure single directional operation and polarisation stability. 10% of the output was tapped off using a 90/10 coupler as signal for the DSHI and the remainder was fed back into the DFB-fibre laser. By injection locking the linear DFB with itself, instabilities were minimised. The system stability was tested by monitoring the output using a fast PD and an RFSA. There was no significant noise observed in the range 0-3GHz and the long term power fluctuations (<1 Hz) were estimated to be < 5%.

The MI- and MZI based DSHIs, shown schematically in Fig. 2(a) and (b), were subsequently tested using delay lines of L1 = 11.6, L2 = 17.6 and L3 = 29.2 km. In the double-pass within the MI, this becomes L1 = 23.1, L2 = 35.2 and L2 = 58.3 km respectively. The feedback in the arms was tuned for maximum interference using an in-line variable optical attenuator (VOA). The beat signal at the AOM shifted frequency was detected using a fast PD and monitored on an RFSA centred at 54.19 MHz for the MI and 27.1 MHz for the MZI. The results can be seen in Fig. 2(a) and (b) in the black, red and blue line respectively. Fits to these results using the Lorentzian Han approximation are shown in green, magenta and yellow respectively. Noting the limitation of a Lorentzian Han-fit to a source with largely Gaussian distribution, it can be seen that the theoretical results have reasonable agreement with experiment.

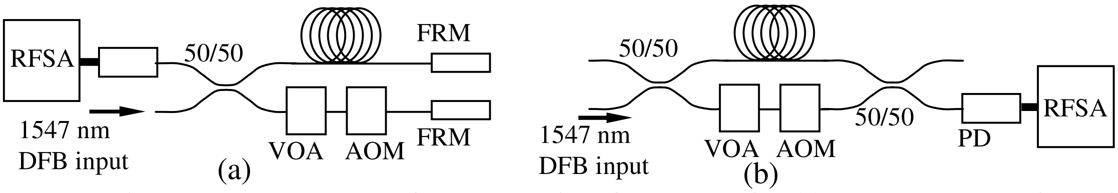

Figure 2. Experimental setup, delayed self-heterodyne interferometer using (a) Faraday rotator mirrors in a Michelson interferometer (MI) and (b) standard unbalanced Mach-Zender interferometer (MZI).

To highlight the region around the nominal central δ-spike, the experimental results for this region are shown in insets in the corresponding graphs in Fig. 3(a) and (b) respectively. In these insets it can be observed that the δ-spike is clearly present for all delay lengths in the MI configuration, whereas for the corresponding MZI results (made

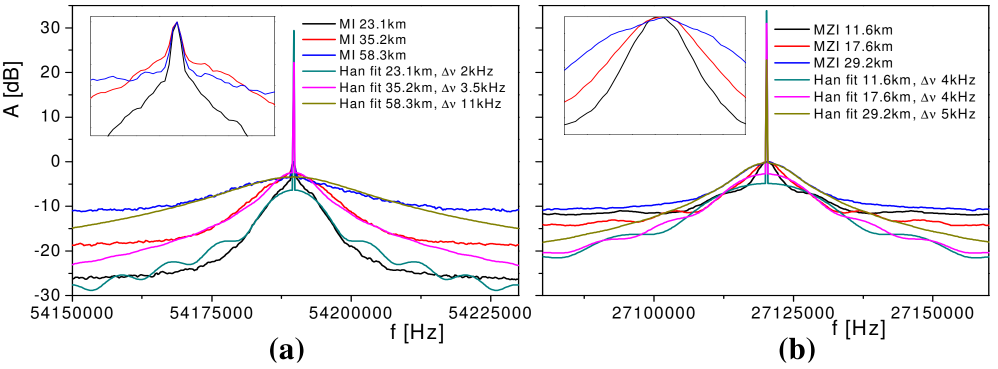

Figure 3. Results from DSHI experiments using the (a) MI and (b) MZI, with corresponding theoretical Han-fits. Insets show experimental results around central position highlighting presence of delta-spike for MI.

using delay lengths half that of the MI), they are absent. The linewidth, $\Delta\upsilon$, extracted from the Han fits represents a convolution of both laser linewidth and system broadening. It is plotted for both interferometers as a function of delay length, L, in Fig. 4. Noting the limited number of data points, the results can be fitted with a similar quadratic function of the measured $\Delta\upsilon$ vs L (shown in red lines) for both cases - system broadening, $d\upsilon/dL$, is 4.9 10-6 Hzm^{-1} and 5.6 10^{-6} Hzm^{-1} for the MZI and MI, respectively. The MI, however, exhibit a >2 kHz reduced offset in bandwidth in comparison to the MZI. Extrapolating to zero propagation length, the measured linewidth using the MZI is $\Delta\upsilon \sim 4$ kHz and with the MI $\Delta\upsilon <$ 1.7 kHz. We know for the MI it is less than 1.7 kHz because we observed the δ spike for the longest path length indicating that coherent mixing is still occurring. This is not true for the MZI where system broadening overwhelms coherence.

3. Discussion

The tests were clearly limited by the low-power DFB laser signal, leading to long averaging times and poor side-lobe resolution. In the MZI case, the absence of a δ spike after only a short length of propagation indicates strong system broadening within the fibre, overwhelming the laser coherence. The MI appears to substantially improve this – the preservation of the δ spike over 60km is 4-6 times the length where the MZI has already lost coherence (despite two passes through an AOM that itself adds noise – we can effectively conclude that the bulk of the broadening is due to the fibre only). This improvement appears larger than the improvement in resolution, a factor of ~ 2.4, but is consistent with the quadratic evolution of the dispersive broadening within the fibre. This quadratic dispersion is consistent with nonlinear dispersion (rather than broadening from thermal and/or chromatic dispersion) such as self phase modulation and potentially cross phase modulation between self phase modulation of the two orthogonal eigenstate axes of the fibre. The Faraday rotators effectively undo this latter contribution.

Unfortunately, the limited data prevents firm identification of the origins of this improvement – for example, the role of gyroscopic effects is not able to be readily ascertained in this present work. Further experiments involving recirculating loops, higher power Master-Oscillator source configurations are planned along with improved fitting of the measured linewidths, using a modification of the Han model to reflect the Gaussian, or Voigt-fits of Lorentzian-Gaussian convolutions (pink noise) of the data.

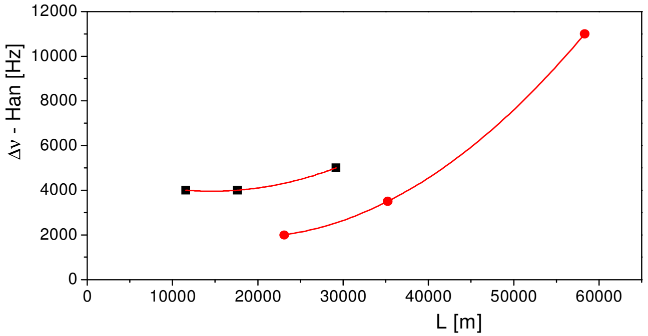

Figure 4. Linewidths estimated from Han fits of DSHI experimental measurements using the MI (red circles) and the MZI (black squares) configurations as a function of delay line length. Red lines are quadratic fits.

4. Conclusions

We have demonstrated that the use of Michelson interferometer configuration with Faraday mirrors significantly reduces net linewidth broadening from the delay coil in a delayed self-heterodyne interferometer (DSHI). The improvement is dramatic: an improvement of ~ 2.4 times (or ~ 1.7 kHz) in the measurement of linewidth, and a sub-coherence length > 6 times the delay line length, probably substantially more.

4. Acknowledgements

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