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Effect of source spectral width and its temporal coherence in the interference pattern of a Mach–Zehnder interferometer

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ABSTRACT

A fiber-based Mach–Zehnder interferometer is designed and tested for its phase characteristics by using a CW tunable laser source. The total phase introduced by the interferometer is modeled by including the linewidth of the input source and the fluctuations of its center wavelength, apart from the path difference in the interferometer. The spectral linewidth of the input laser contributing to the observed interference is found to depend on this path difference. This emphasizes the need for optimal path differences to overcome the coherence limitations of the source. We are thus able to extract the extent of phase correlation present in the input source, and hence its temporal coherence characteristics, from the interference pattern.

1. Introduction

Optical fiber-based interferometers are very sensitive devices which can sense very small phase changes occurring in an optical fiber. The phase changes occur due to changes in factors such as the path length difference, temperature, pressure, force, heat, refractive index, vibration, bend and strain in the optical fiber [1–4]. Apart from such sensing applications, the phase can also be influenced by the input source parameters such as the wavelength and spectral width [5]. The total phase change can be characterized from the interference pattern in order to get the source information [6,7]. Fiber interferometers can be designed in many configurations such as the Michelson interferometer [8], Sagnac interferometer [9], and Mach–Zehnder interferometer [2]. Depending on the requirements, all are useful in their own working domains.

A fiber interferometer is a good tool to measure the coherence property of any fiber-coupled light source. The output of the interferometer will show interference features if the temporal coherence length of the source is larger than the path difference between the two interfering arm lengths [10]. Even though the physical path difference may remain constant during an experiment, the phase difference between the two arms can depend on several factors such as the center wavelength of the input laser, fluctuation in wavelength of the input laser, the spectral width of the input laser and any phase imbalance in the couplers.

In the earlier reports, interferometric techniques have been used to study the temporal coherence of *pulsed* sources of different spectral width [11–13]. Depending on the spectral width and the pulse duration, the path difference of the interferometer was chosen to get a larger visibility in the interference pattern. In [11], it was observed that if spectral output of a source is not fully temporally coherent, only a fraction of the spectral width contributes to the coherence. In [12], the complex degree of coherence was found to be different for two different pulse widths observed in the same range of path length difference. For larger pulse durations, the complex degree of coherence was poorer than that for the smaller pulse durations, and this was also observed in [13] by recording the visibility of the interference pattern. In CW sources, however, the pulse duration limiting the path difference is not relevant. The effect will be entirely from the spectral content of the source.

We have recently developed a CW fiber-optic source with a broadband output and we extracted the extent of its spectral width that contributes to the complex degree of temporal coherence. We used a Mach–Zehnder interferometer (MZI) with fixed arm lengths and analyzed the interference pattern at its output to get the effect of source spectral width [14]. The path difference in the MZI is chosen to be small so that we get a large visibility in the interference pattern. The calibration of the MZI is discussed in the present work wherein a standard tunable laser source is used as the input. The interference pattern is recorded whenever the phase introduced by the MZI is varied. When the path difference is kept fixed, the phase variations due to the input source parameters play a role in the total phase variation. The spectral width of the source is significant for the interference only when

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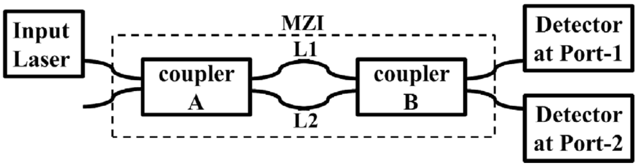

Fig. 1. Schematic of the experimental set-up of MZI. The box shown by dashed line represents the interferometer.

the path length difference is very small and its relevance is completely lost for larger path length differences. The fixed-length MZI is a device which is useful to extract the spectral width of the input source which contributes to its coherence property. We have identified the source spectral width which leads to a large visibility of the interference pattern for the chosen path length difference of the interferometer. Since the MZI has two individual interfering paths, it is very easy to characterize the total phase in this configuration as both the interfering beams can be controlled individually. It contains only two fiber couplers combined through splicing and the beam propagation is always in one direction. Fiber-based MZI is also important due to its small footprint and simple design. In the first part, we have characterized a tunable laser source in order to calibrate the MZI. In the second part, we re-visit the theoretical understanding on the functioning of MZI. Finally, we extract the line-width of the laser source from this model using the experimental results from the MZI.

2. Experimental details

Fig. 1 shows the schematic of the experimental set-up of MZI. Two 2 x 2 fiber couplers, named A and B, are combined through splicing. The output of the first coupler A is the input to the second coupler B. The light source which is to be characterized is connected to one of the input ports of coupler A and the outputs from the two ports of coupler B are measured by the detectors at port-1 and port-2. The input laser source can be a laser having a temporal coherence length equal to or greater than the path difference (L1-L2) between the two arms of the interferometer. The detector is an optical spectrum analyser (OSA) and/or a power meter. The output powers of both the couplers A and B are measured individually and found to be in the ratio of 70:30 and 60:40 respectively at their direct and cross ports. The arm lengths of each coupler are fixed and the physical path difference (L1-L2) is very small and is approximately 5 ± 2 mm. Here, we did not use any device (such as a phase modulator) to control the phase in the set-up. As the phase difference between the arms depends on the wavelength, any variation in the input wavelength will introduce a phase difference in the set-up even though the path difference is kept fixed.

Apart from the difference in the physical paths, there can be additional contributions to phase due to other terms such as the spectral width of input laser and fluctuations in the polarization of the fields during propagation. Since we did not use the polarization maintaining fiber or any polarization controller in the set-up, there is a possibility of phase contribution due to polarization changes too. Any significant fluctuation in polarization would lead to reduced visibility of the interferometer. By tuning the wavelength of the source, the output powers of the MZI are recorded at port-1 and port-2 which show maxima and minima at different wavelengths. Fluctuation in the output power during measurement with a power meter is found to be less than 1 dBm. By observing the interfered output, one can get the visibility over a wavelength range. The visibility is a measure of the degree of coherence [10] and this quantity or coherence time/coherence length is decided by the nature of light generation in a source. For lasers with transform-limited spectra, the coherence length is inversely proportional to the spectral width of the source. Hence, one can comment on the coherence of the input source by observing the visibility of its interference pattern as a function of wavelength.

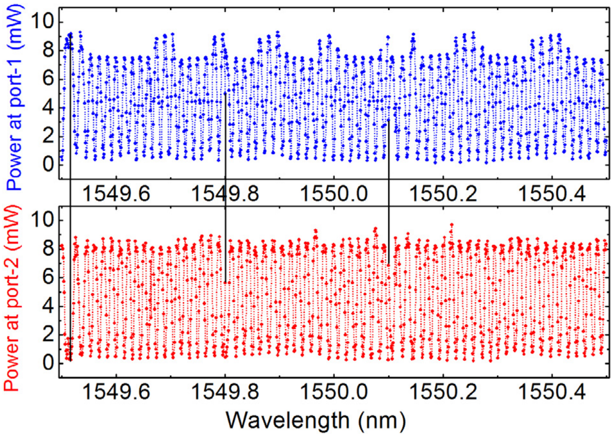

Fig. 2. The MZI output at port-1 and port-2 is measured using a tunable laser on a power meter. The points joined by the line show the measured data. The three vertical lines are drawn to compare the outputs at port-1 and port-2 at three different wavelengths.

We have used a tunable laser (Yenista Optics – TLS-AG) with a wavelength tunability of 36 nm and an output power of 20 mW as the input source to our MZI set-up, and observed the interference pattern both on the power meter and OSA. The powers at port-1 and port-2 are measured on the power meter when the laser wavelength is tuned from 1549.500 to 1550.500 nm in steps of 0.001 nm. The results show a periodic change with the wavelength of the laser and the maxima and minima in the powers are exactly complementary between the two ports (Fig. 2). Due to propagation loss through the fibers and the insertion loss of the couplers, the maximum power at the output is obtained as 9.10 mW and the minimum is 0.28 mW, giving an average visibility of 94%.

It is clearly seen in Fig. 2 that the outputs at port-1 and port-2 follow the trend expected in an interferometer. To emphasize this feature seen in the experiment, three vertical lines are shown for three different data points (wavelengths) in Fig. 2 in order to compare the outputs at port-1 and port-2. For the first vertical line, the output is at a maximum (9.28 mW) in port-1 and at a minimum (0.34 mW) in port-2. For the second vertical line, the output is at the half-maximum point with a power of 5 mW at port-1 and the same value is obtained at port-2. For the third vertical line, the output is 3 mW at port-1 and 7 mW at port-2. The maxima in port-1 are found to match precisely with the minima in port-2 and vice-versa at any given wavelength, within the experimental limitations.

The average period of occurrence of maxima in port-1 is 0.016 nm and the average period in port-2 is also 0.016 nm. The maxima and minima in intensity are obtained as a result of constructive and destructive interference with respect to the phase variation occurring in the MZI. In our case, the phase due to the arm length/path length of the interferometer is fixed. Therefore, the phase variation is likely to be from the wavelength tuning of the input laser. The period of maxima and minima with wavelength is expected to be 0.33 nm using a delta function spectrum of input laser in this experimental arrangement, but the variation seen with wavelength in the experiment is much more rapid indicating the role of some other parameter. Apart from the change in wavelength, the phase contribution is also likely to arise from other factors such as the fluctuation in the wavelength of the laser and the relative phases of the wavelengths present within the spectral width of the laser at each of its wavelength settings. The change in phase due to such factors leads to the variation in the output power measured at the power meter for each wavelength setting of the input laser source.

The output of the MZI measured at the two ports using the OSA is shown in Fig. 3 as dotted and dashed lines at six different wavelength settings of the input laser. The effect is visible as in Fig. 2, and the role of interference is clear. The spectrum of the input laser directly measured on the OSA is also shown in Fig. 3 at each of these wavelengths