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COMMON MODE COMPENSATION IN FIBER OPTIC INTERFEROMETRIC SENSOR WITH LESS COHERENT LIGHT

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Abstract

Sorce noise effect in 1.5 Mach-Zehnder(MZ) interferometer is analyzed. It is shown numerically that with fine adjustments to the feedback gain and intial phase biases, the operating point of the interferometer to achieve common mode compensation can be made to lie in a region where the measurand sensitivity is greater than it would be in a conventional Mach-Zehnder interferometer even if the source is less coherent.

I. Introduction

Common mode compensation(CMC) consists of arranging the paths in an interferometer so as to minimize or eliminate the effects of purturbations, which affect all optical paths in proportion to their optical path lengths[1]. Spatially uniform temperature and pressure fluctuations and fluctuations in the source wavelength are examples of common mode purturbations that are important error sources for fiber-optic sensors. The 'CMC' was achieved by proposed 1.5 MZ interferpmeter[2,3]

The performance of any optcal fiber interferometric sensor is influenced by source noise. In many implementations of these sensors, light is being split and,after experiencing different time delays, recombined using evanescent type directional couplers wich add light on an amplitude basis. Thus, the interferometric effect can take place, and in particular, the source phase noise is convertd to intensity noise which appears at the output, thereby degrading the available dynamic range.[4]

In actual applications, laser diode(less coherent source) is preferable to the light source of fiber optic sensors.

In this work, we analyze the source noise effect in 1.5 MZ interferometer. And we will show that the interferometer still can achieve CMC and have high sensitivity under less coherent excitation.

II. 1.5 MZ interferometer

The optical circuit of the 1.5 MZ interferometer is schematically shown in Fig.1. Light enters the circuit at the 3dB coupler C_3. The upper optical path leaving C_3 provides a reference optical power level for the photodetector D_2. This reference level is not necessary if the power output of the light source LS is extremely stable over time, but it is included here for the sake of completeness. The photodetector D_1 is of same type as D_2. The ouput of the ratio circuit is proportional to the transmittance of the optical fiber path from the lower right output port of C_2 to the upper right output port of C_2. In the conventional MZ sensor typical prior art[4], no fiber optic compensating circuit or electrical feedback circuit would be used. Instead the lower right output of C_3 would be connected directly to the upper left input of C_0 by an optical fiber.

In compensating and sensing circuits, initial phase biases can be controlled by applying voltages to the phase shifters exactly the same as in non feed-back 1.5 MZ interferometer. Thus the relative phase shifts between the lower and upper optical paths in compensating circuit is given by

$$\theta = \frac{2\pi}{\lambda} n_e (L_{s1}-L_{r1}) + \Delta\theta$$
$$= 2\pi M_1 + \eta \qquad (1)$$

The relaive phase shift for the optic sensor circuit is

$$\rho = \frac{2\pi}{\lambda} n_e (L_{s2}-L_{r2}) + \Delta\rho + \delta\rho$$

where $\Delta\theta$ and $\Delta\rho$ are phase shifts adjusted by external voltages, M_1 and M_2 are any integers, η and ξ are modulo phases, and $\delta\rho$ is linearly proportional to the transmittance, $\delta\rho$ can be given by:

(3)

where k, the feedback gain, depends on the electronics and the electrooptic modulator characteristics.

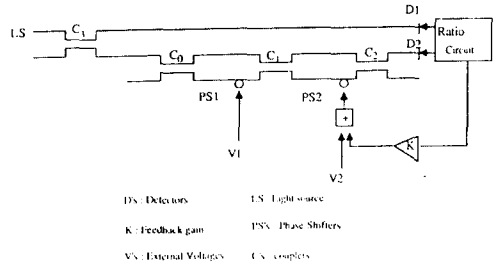

Fig.1. Schmatic diagram of 1.5 MZ interferometer

Ⅲ. Source noise effect

1. Laser source characterization

In general, the emission field of the optical source varies with time in a random fashion, and is, statistical in nature.[5] For a given polarization state, the emission field generally fluctuates randomly in both phase and amplitude(intensity) with possible correlation between them.[6] This randomness can be fully described by statistics. However, due to the damping of the amplitude fluctuations by gain saturation[6], semiconductor laser sources operating well above threshold exhibit negligible amplitude(intensity) fluctuations near the lasing frequency. As a result, the dominant contribution to line broadening comes from the randomness of the phase fluctuations. Thus, we can assume that the optical field $E_{in}(t)$ for a single axial mode of the laser source is of the form

$$E_{in}(t)=E_1\exp(-j\omega_0 t+\phi(t)) \qquad (4)$$

where E_1 is amplitude which is assumed to constant, ω_0 is the optical angular center frequency, $\Phi(t)$ is the time varying random phase, and $j=\sqrt{-1}$. It is usually assumed that the phase under goes a random-walk process[7]. More specipically, it is common to take the Wiener-Levy random process as a statistical model for random phase fluctions of laser light[7]. According to the Wiener-Levy process, its first fluctuations are stationary and independent. Defining the first increment of the phase by $\Delta\Phi=\Phi(t_1)-\Phi(t_2)$ where t_1 and t_2 are two arbitrary constants, we conclude that $\Delta\Phi$ is a zero mean Gaussion random process, with its probability density function $p(\Delta\Phi)$ as shown below;

$$p(\Delta\phi)=\frac{1}{\sqrt{2\pi}\sigma}e^{-[\Delta\phi^2/2\sigma^2]} \qquad (5)$$

where σ^2 is the variance of the phase difference which depends on the time difference $\tau=t_1-t_2$. The "structure function" are certain average quantities which are frequently used in stochastic analysis[8]. The angle bracket denotes the ensemble average. The self coherence function of the laser emission field(which is the input of the sensor) is of the form

$$< E_{in}(t)\, E_{in}^*(t-\tau) > = E_1^2\, e^{j\omega_0 t} < e^{j\Delta\phi(\tau)} > \qquad (6)$$

where* is the complex conjugate. Since

$$< e^{j(\Delta\phi)} > = \int e^{j\Delta\phi}\, p(\Delta\phi)\, d(\Delta\phi) \qquad (7)$$

and assuming that

$$D_\phi(\tau) = 2\frac{|\tau|}{t_c}, \qquad (8)$$

where t_c is the source coherence time, Eq.(6) becomes

$$< E_{in}(t)\, E_{in}^*(t-\tau) > = E_1^2\, e^{j\omega_0 t}\exp(-|\tau|/t_c) \ . \qquad (9)$$

The field spectrum given by the Fourier transform of the autocovariance function is

$$S(f) = \frac{2\tau_c}{1+[\,2\pi\tau_c(f-f_0)\,]^2} \qquad (10)$$

where f is the optical frequency, and f_0 is the optical center frequency. This form of the self coherence function(autocovariance function) is associated with a lorenzian line shape of the optical spectrum.

2. Source noise effect in 1.5 MZ interferometer

Based on previous discussions, the time averaged transmittance of the MZ interferometer with source phase noise becomes

$$<T> = T_{max}[\,1+ q\cos\emptyset] \qquad (11)$$

where $q=\exp(-|\Phi/\omega t_c|$, t_c is coherence, time, and T_{max} is the maximum value of the MZ interferometer transmittance.

Similaily, time averaged transmittance of the feedback 1.5 MZ interferometer can be derived:

$$E_{out} = \frac{1}{2\sqrt{2}}t_r^3\sum_{l\,n=0}^{1} h_{l\,n}\, E_{in}\,(\,t-l\,\Delta_1\ \ t-n\,\Delta_2\,) \qquad (12)$$

where
$$h_{0,0} = 1$$
$$h_{1,0} = -1$$
$$h_{0,1} = -1$$
$$h_{1,1} = -1$$

Output intensity I_{out} is $|E_{out}(t)|^2$, and using autocovariance of the field in Eq.(8), the time averaged transmittance becomes

$$< T > = <\frac{|\,E_{out}\,|^2}{|\,E_{in}\,|^2}>$$

$$= T_0[\,1+0.5\,A\cos(\,\theta-\rho\,)-0.5\,B\cos(\,\theta+\rho\,)\,] \qquad (12)$$

where

$$T_0 = 0.5\ t_0^6$$

$$A = \exp\,[-(|\theta-\rho|/\omega\tau_c)]$$

$$B = \exp\,[-(|\theta+\rho|/\omega\tau_c)]$$

$$\rho = \rho_0 + k< T >$$

Coherence factors of this optical device, A and B, limit the degree of coherence(visibility) and the sensitivity. The complex degree of coherence V is given by[10]

$$V = 0.5\,[\,A\cos(\,\theta-\rho\,)-B\cos(\,\theta+\rho\,)] \qquad (14)$$

The visibility or degree of coherence is represented by the absolute value of V with $|V| \le 1$[10]. The transmittance <T> can be modified as

$$< T > = 0.5\,To\,[\,1+0.5C\sin(\,\rho_0+k<T>+\zeta\,)\,] \qquad (15)$$

where

$$\alpha = (\,A-B)\cos(\theta)$$

$$\beta = (\,A+B\,)\sin(\theta)$$

$$C = \sqrt{\alpha^2+\beta^2}$$

$$= \sqrt{A^2+B^2-2AB\cos(2\theta)}$$

$$\zeta = \tan^{-1}[\frac{\alpha}{\beta}]$$

Fig.2 shows that the transmittance of the MZ and the 1.5 MZ interferometer with k=2.5 and $\omega\tau_c=2\pi\times10^4$. In Fig.3, k is increased to 3.5 such that the interferometer compensate the degraded sensitivity due to source noise

The common mode compensation condition can be obtain:

$$f_{cm} = \frac{\partial T}{\partial \theta}\theta + \frac{\partial T}{\partial \rho}\rho$$

$$= W \sin(k\langle T\rangle + \rho_o + \xi + \chi) \qquad (16)$$

where $W = \sqrt{U^2 + V^2}$

$$U = 0.5\, T_o\, C\, [\, \rho\, (1 + \frac{\partial \xi}{\partial \rho} + q\frac{\partial \xi}{\partial \theta}]$$

$$V = 0.5\, T_o\, [\frac{\partial C}{\partial \rho} + \frac{\partial C}{\partial \theta}]$$

$$\chi = \tan^{-1}\{C\, [\, \rho\, (1 + \frac{\partial \xi}{\partial \rho} + q\frac{\partial \xi}{\partial \theta})]/(\frac{\partial C}{\partial \rho} + \frac{\partial C}{\partial \theta})\}$$

For $f_{cm} = 0$,

$$k\langle T\rangle + \rho_o + \xi + \chi = N\pi \qquad (17)$$

where N is any integer. This is the general expression for the "CMC" condition under any coherence excitation by increasing the feedback point. Fig.5 and 6 suggest a simple way to find the point to achieve "CMC". With fine adjustments to k or θ, the operating point for common mode compensation can be made to lie in a region where measurand sensitivity is much higher than it would be in a MZ interferometer under less coherent excitation.

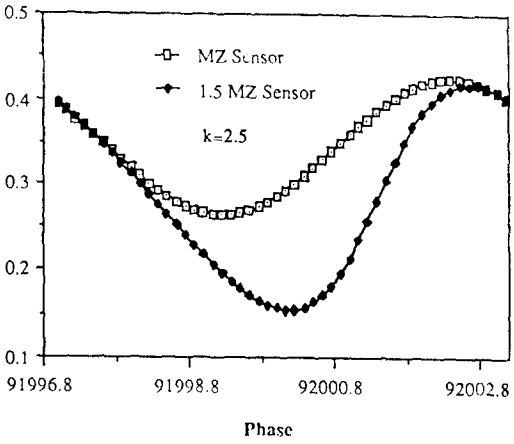

Fig.2 Transmittance of the MZ and the 1.5 MZ interferometer when $\omega t_o = 2\pi \times 10^4$ and k=2.5

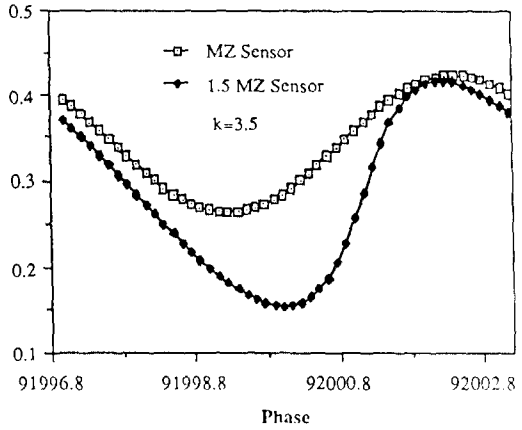

Fig.3 Transmittance of the MZ and the 1.5 MZ interferometer when $\omega t_o = 2\pi \times 10^4$ and k=3.5

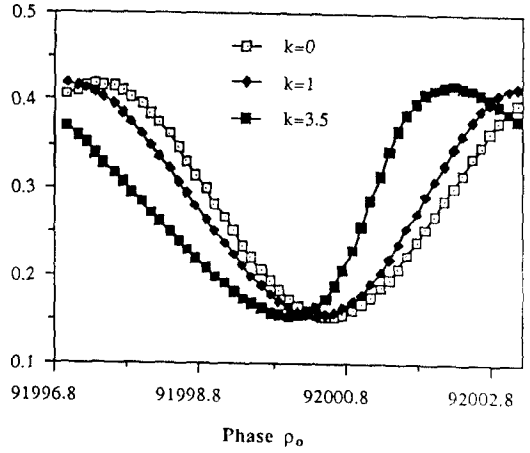

Fig.4 Transmittance vs. ρ_o for different values of feedback gain when $\omega t_o = 2\pi \times 10^4$

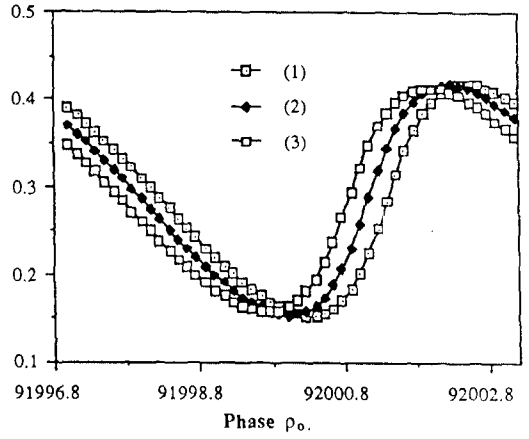

Fig.5 Transmittance vs. ρ_o for different values of θ when k = 3.5 and $\omega t_o = 2\pi \times 10^4$
(1) $10^5 + 0.25\pi + 0.3$ (2) $10^5 + 0.25\pi$
(3) $10^5 + 0.25\pi - 0.3$

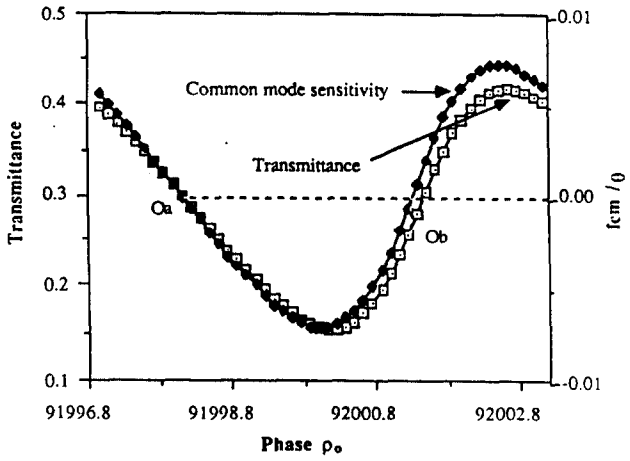

Fig.6 Transmittance and common mode sensitivity vs. ρ_o when $\theta = 10^5 + 0.25\pi$, k=3.5 and $\omega t_c = 2\pi \times 10^4$ O_a and O_b are the common mode compensating points.

Ⅳ. Conclusion

We analyze the source noise effect in 1.5 MZ interferometer under less coherent excitation. With less coherence in the source a higher value of feedback gain allows the interferometer to achieve high sensitivity.

Futhermore it is possible to find a set of electronically controllable parameters(external voltages to PZT) and amplifier gain lead to high measurand sensitivity and low common mode sensitivity.

In the next work, we will show experimenally that the 1.5 MZ interferomter can achieve the above results.

Reference

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