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Design And Analysis Of Sagnac Loop Frequency Characteristics

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Abstract: The Sagnac interferometer consists of optical components which first split light into two beams and then route each of these beams in opposite directions around a common optical path. After propagating around the optical path, both beams are recombined on a detector or screen where the resulting interference pattern can be observed The construction of fiber optic interferometers is similar to the construction of classic optical interferometers with open light flux. They are designed for measurements of phase shift caused by an interaction between external fields and optical fiber. The value of characteristic frequency f_r depends on the disturbance position. Exactly, it depends on the difference T_D Between times of reaching the interference place by wave fronts of two counter running waves with distributed phase. We can see that if the sensing loop length is increased, the characteristic frequency is decreased

I. INTRODUCTION

The optical sensor systems presented is based on the use and understanding of a reciprocal path interferometer, known as the Sagnac. In its simplest form, the Sagnac interferometer consists of optical components which first split light into two beams and then route each of these beams in opposite directions around a common optical path. After propagating around the optical path, both beams are recombined on a detector or screen where the resulting interference pattern can be observed. Fig 1 shows a simple bulk-optical configuration forming a Sagnac interferometer [2].

Light from a source is split using a half silvered mirror. 100% reflecting mirrors are then used to route the transmitted and reflected beams around a common free-space optical path before they are again incident on the half silvered mirror. This in turn combines the two beams on a screen allowing the interference pattern to be observed. Optical structures similar to this formed some of the first Sagnac interferometers

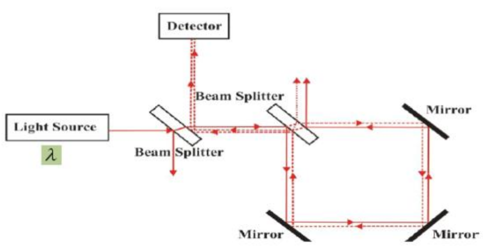

Figure 1: Basic Sagnac interferometer

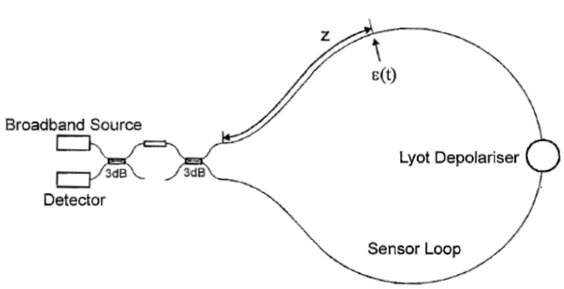

Figure2: Fiber optic Sagnac interferometer

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Schematic of the Sagnac interferometer, realized from fiber optic components. A broadband low-coherent source is used to reduce the effects of interference from back-scattered light, arising from Rayleigh and Fresnel scattering. Using a Lyot depolarizer, the state of polarization is effectively randomized in the wavelength domain, hence reducing polarization fading effects by averaging over source bandwidth.

Fiber optic components however offer convenient alternative ways to form an interferometer of this type. The biconically-fused fiber coupler is a commonly used device that couples incident light into each of two output ports, whilst presenting very low insertion and polarization dependent loss. The fraction of light coupled to each of the output arms need not necessarily be equal but for the Sagnac 50/50 (or 3db) couplers are usually used. Consider what happens in the optical configuration shown in Fig 2. Light emitted by a broadband source is divided by the first 3db coupler. Since one output arm of this first coupler is unused, 50% of the light is lost. The light in the other output arm however is then plane polarized by propagation through a fiber-based polarizer. This plane polarized light then encounters a second 3db coupler and is again split equally into two wave trains, one propagating clockwise and the other counter-clockwise around a loop of fiber defining an optical path. After propagating around the loop the two wave-trains are recombined by the same 3db coupler through which they were launched into the loop. The combined light again passes through the polarizer and is incident on a detector where the intensity of the interference signals may be observed (again incurring a 50% loss into the source arm). Comparing this structure with the

Initially presented bulk-optics architecture we see that the second 3db coupler performs the function of the half-silvered mirror and that the first simply allows the interference pattern to be observed on a detector. The mirrors have now been replaced with a coil of single mode optical fiber which can be bent into a loop to define the optical path taken by counter-propagating beams.

II. Spatial And Frequency Analysis Of Sagnac Loop

The construction of fiber optic interferometers is similar to the construction of classic optical interferometers with open light flux. They are designed for measurements of phase shift caused by an interaction between external fields and optical fiber. The optical configuration of interferometers, namely propagation of light in closed optical waveguide, is adopted from classical interferometry as well. The main components of fiber optic interferometers are: a semiconductor laser, a coupler, a detector and a demodulator. The above mentioned basic metrological function is fulfilled by all interferometers irrespective of configuration, except the loop interferometer which has an optical circuit in form of closed loop. Two interfering optical waves propagate in the same optical path but in opposite directions. Therefore both waves undergo phase distortion to the similar extent. The moment when a distortion fore-part reaches the place of interference depends on position of phase disturbance. For this reason the modulation of intensity of interferometer response depends monotonically on a disturbance position along the loop [4].

III. Spatial Characteristic Of Loop Interferometer

Let us assume that phase modulation occurs in the given segment of optical fiber of any length. Modulator may be located in any place of optical fiber loop,

E.g., as it is presented in Fig. 3.

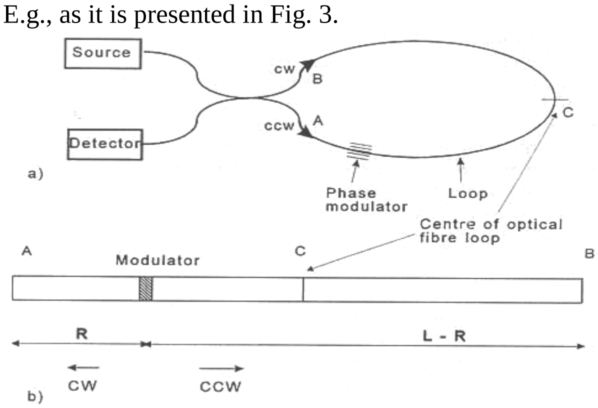

Figure 3: modulation is applied

We introduce here following notations: T_1 = (Rn/c) stands for the time in which the disturbance of CW wave reaches the coupler, T_2 = (L—R)n/c is the same time for CCW wave, $T_D = |T_1 - T_2|$=(2R-L)n/c stands for the difference of reaching times for both

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Waves, $T_D = T_1 - T_2$=Ln/C Is The Time Of Loop Circulation By Any Wave ,N=1.45 Is The Refractive Index Of Fiber Core ,C = 3 x10^8m/S Is The Light Velocity, R Is The Phase Modulation Position From Coupler And L Is The Loop Length. Using These Notations One May Express Transfer Function As [4]:

$I(T) = 1 + \mathrm{Cos}[\Phi \,\mathrm{Sin}\, \Omega(T - T_1) - \Phi \,\mathrm{Sin}\, \Omega(T - T_2) + \Delta\Phi]$ ……… [3.1]

Where Ω The Frequency Of Modulator Pulsation Is, Φ Is The Magnitude Of Phase Modulation, And $\Delta\Phi = \Phi_1 - \Phi_2$ Is The Desired Phase Shift. Expression [3.1] May Be Transformed Into:

$I(T) = 1 + \mathrm{Cos}[2\varphi \,\mathrm{Sin}(\Omega T_D/2)\,\mathrm{Cos}\,\Delta\emptyset - \mathrm{Sin}[2\varphi\,\mathrm{Sin}\left(\frac{\Omega T_D}{2}\right)\mathrm{Cos}\,\Omega(T - T/2)]\,\mathrm{Sin}\,\Delta\Phi$ …….. [3.2]

Using Bessel Functions Of First Kind One May Describe The Series Expansion Of Sine And Cosine Functions. Taking Into Account Only The First Terms Of These Expansions We Obtain An Expression Showing The Form Of First Harmonics Of Even And Odd Series.

$I(T) = 1 + [J_0(\emptyset_E + 2J_2(\emptyset_E)\,\mathrm{Cos}\,2\omega(T - T/2)]\,\mathrm{Cos}\,\Delta\Phi - [2J_1(\emptyset_E\,\mathrm{Cos}\,\Omega(T - T/2)]\,\mathrm{Sin}\,\Delta\Phi$ …[3.3]

Where $J_1(\emptyset_E)$ Is Bessel Function And $\emptyset_E = 2\varphi\,\mathrm{Sin}(\Omega T_D/2)$.Operating Point In The Quadrature May Be Fixed By Introducing The Phase Shift Equal To$\Delta\Phi = \Pi/2$. Then They Obtained Response Signal Has A Form Of The First Harmonic:

$I(T) = 1 - 2J_1[2\varphi\,\mathrm{Sin}(\frac{\Omega T_D}{2})]\,\mathrm{Cos}\,\Omega(T - \frac{T}{2})$ …………… [3.4]

From Equ [3.4] One Can Found That The Response Signal I (T) Is Proportional To The Phase Modulation Function $\emptyset(T)$ And COS [Ω(T— T/2)] Is Constant For A Given System. When An Argument Of Bessel Function Is Equal To 1.84 Rad, Then Function I (T) Achieves Its Maximum [4]:

$J_1[2\varphi\,\mathrm{Sin}(\frac{\Omega T_D}{2})] = J_1\,(1.84)$ …… [3.5]

For Small Values Of Phase Modulation, Ranging 0.1 Rad. One Should Assume $J_1(\propto) = \propto$. Therefore The Variable Component Of The Signal Is Given By:

$I(T) \approx 4\varphi\,\mathrm{Sin}(\,\Omega T_D/2)$ ……… [3.6]

The Next Simplification May Be Done If $\left(\frac{\Omega T_D}{2}\right) \ll \Pi/2$:

$I(T) = \frac{4\varphi\omega T_D}{2} = 2\varphi\omega T_D = \frac{4\pi f|L-2R|N}{C}$ ……….. [3.7]

Thus For Small Values Of Phase Modulation And Small Modulation Frequencies, The Interferometer Response Is Proportional To The Product Of Modulation Frequency F And A Difference Of Reaching Times Of Both Waves

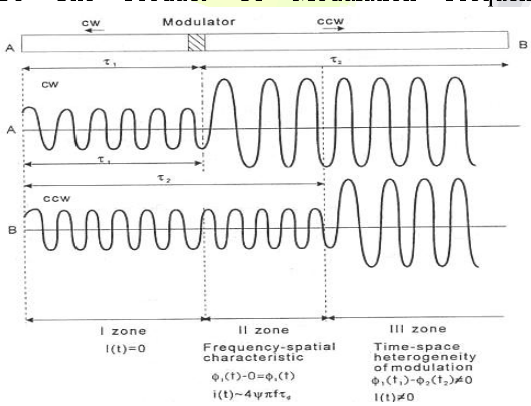

Figure 4

Fronts of both waves with disturbed phase reach the place of interference in different time. During T_1 Interval, the interference of waves without phase modulation takes place. The response signal is therefore equal to zero. In other words, the detector current is constant. This is the first modulation zone in Fig. 4. In the interval T_D , i.e., before wave fronts of CW and CCW waves reach the coupler, the interference of phase modulated CW wave with undisturbed CCW wave takes place. This is the same type of interference as in two-arm interferometer . In this time interval the basic interference process, introducing the main contribution to response characteristic of loop interferometer, occurs. After wave front of disturbed CCW wave reaches the coupler, these both phase modulated waves interfere. Their contribution to the output signal should be equal to zero in the ideal case, i.e., when $\emptyset_1(T) = \emptyset_2(T)$This condition will not be fulfilled only if the modulation is un homogeneous in space or time. If the modulator is placed nearby the coupler (i.e., R= 0), then $T_D = \tau$ and the signal i (t) has maximum for a given disturbance

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frequency. If the modulator is moved away from the centre of loop length, the signal decreases to zero in the loop centre (i.e., for r = l/2, see equ [3.7].

If the modulator is placed exactly in the loop centre, both waves will reach it in the same time. In the similar way wave fronts reach the coupler after τ/2 intervals. Both waves have then the same phase shift. Assuming that the contribution from spatial and time modulation difference of those waves may be neglected, one can found zero response signal i(r = l/2, t) =0 [4].

IV. Frequency Characteristic Of Loop Interferometer

Let us return to the expression describing the magnitude of variable component of loop interferometer response on disturbance signal:

$I(T) = 2J_1[2\varphi \, \mathrm{Sin}(\omega T_D /2)$ ….. [4.1]

We will analyze more thoroughly the influence of modulation frequency on the response characteristic. First, we should find the location of extremes of transfer function on the frequency scale Maximum of i (t) corresponds to the Bessel function argument equal to 1.84 rad:

$2\varphi \, \mathrm{Sin}(\omega T_D /2) = 1.84$ ………. [4.2]

Where $\frac{\Omega T_D}{2} = \frac{N\pi}{2}$, $N = 1,2,3, \ldots\ldots$. Thus the modulation frequency is given by:

$F = Nc/(2|2R - L|N)$ …………. [4.3]

The interferometer response i (t) has its maximum values for N=1, 3… (Odd numbers) and zero values for N=2, 4 … (Even numbers). The frequency response of loop interferometer is therefore periodic function with maxima and minima described by equ [4.3].The frequency value for an extreme depends on disturbance position R. For R =0(disturbance close to the loop input) and loop length of 160Km, one may obtain $i(t)_{max}$ at f=633.44 Hz and $i(t)_{min}$ at f=1.27khz. The spectral characteristics of loop interferometer with L=160Km is presented in fig [5]. Maxima and minima occur for each 1.27 khz.

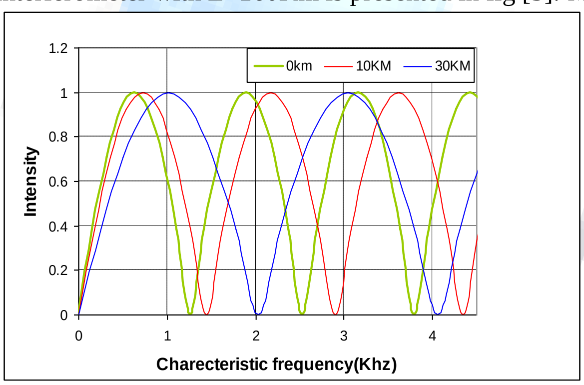

Figure [5]:
spectral characteristics of loop interferometer (L=160Km)

The frequency $f_r = 1/T_R = 1/\tau$ is called characteristic resonance frequency of loop interferometer. The interferometer response to the phase modulation with resonance frequency is zero despite of the magnitude of this modulation.

$|I(t)|_{F=F_R} = 2\varphi \, \mathrm{Sin}\, 2\pi T_D F_R = 0$ … [4.4]

It means that assuming frequency f=1/τ we will not observe any phase shift on the interferometer output. One can found from fig [5] that i (t) →0 if f→0 or $f \to f_r$ .This effect is called frequency discrimination and it means that interferometric detection of low frequency phase modulations is not effective and impossible for f→0 [4].

5. RESULTS

The value of characteristic frequency f_r depends on the disturbance position. Exactly, it depends on the difference T_D Between times of reaching the interference place by wave fronts of two counter running waves with distributed phase. Fig [6] dependence of characteristic frequency f_r on disturbance position is presented, according to equ [4.3]. The physical interpretation of characteristic frequency derives from equ [4.3], where $F_R = \frac{N}{2T_D} = 1/T_R$. The null frequency components in different sensing loops are shown in fig [6].

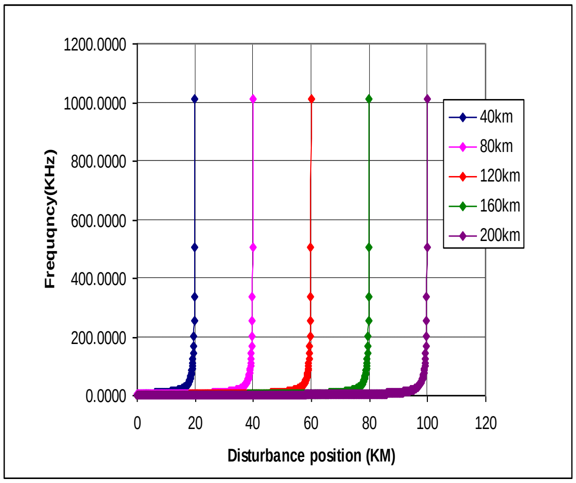

Figure: [6]: null frequency

The maximum interference occurs at different positions for different sensing loop length is to be plotted in fig [7].

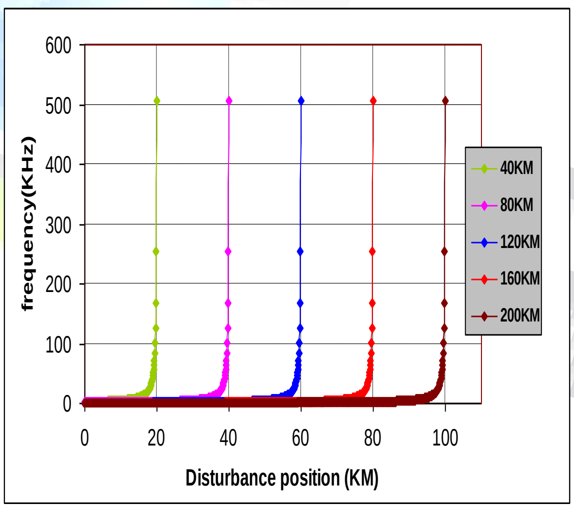

Figure [7]: characteristic frequency

From the below graph it was seen that varying the loop length from 40Km to 200Km the characteristic frequency is to be goes down. This is shown in fig [8].

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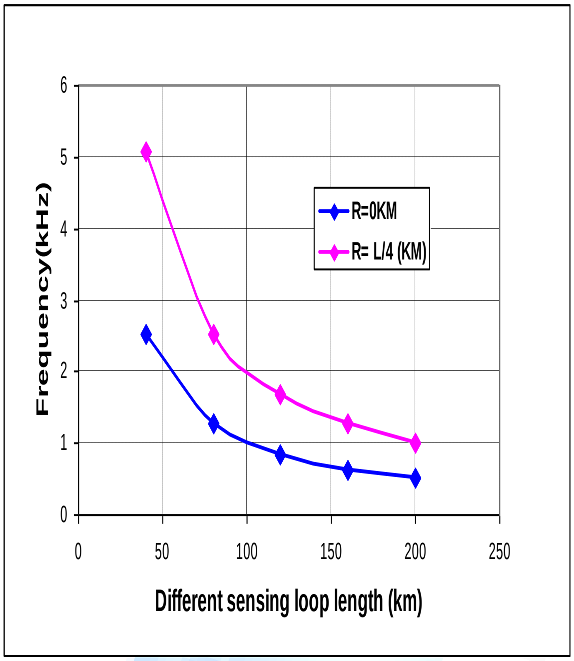

Fig [8]: sensing loop length vs Frequency

Loop length	40Km	80Km	120Km	160Km	200Km
F max(KHZ)	2.5337	1.26689	0.84459	0.63344	0.50675

From this table we can see that if the sensing loop length is increased, the characteristic frequency is decreased.

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