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Noise Reduction of a Novel Phase-Locked Coherent Optical Phase Demodulator

G. M. Helaluddin
Department of Physics, Sidho-Kanho-Birsha University,
P.O. & Dist. Purulia, West Bengal, India, Pin 723101
Email: helaluddindgc@gmail.com

***Abstract* − This paper includes the novel cancellation technique for reducing phase noise and shot noise with the relaxation of stringent line width requirements and power requirements of optical sources in proposed phase-locked coherent demodulator for phase modulated analog optical link. The theoretical analysis has been carried out considering finite loop propagation delay and additional phase modulation at LO laser output. The technique of cancellation significantly compensates effect of loop propagation delay and improves line width requirement up to 29.6%. Furthermore, the nonlinear tracking of LO phase modulation reduces power requirement to 2.8dBm in terms of PNB.**

***Keywords* – LO: Local Oscillator, DFB: Distributed Feedback, PNB: Number of Photons Per Bit, SNR: Shot Noise Reduction, PNR: Phase Noise Reduction.**

I. Introduction

Optical phase locking techniques for coherent detection have great importance as found in the beginning of 90s [1-15] in order to enhance the receiver sensitivity in various techniques. A survey of different linearization cancellation techniques can be found [16]. So far, linearization techniques have been employed to study the system performance in terms of different noises, i.e. shot noise of quantum detection process of photo detector and phase noise due to spontaneous emission of optical sources. But it was not studied earlier that how the LO phase modulator reduces the noises of receiver to increase the sensitivity and also the effect of the receiver stability. Thus, in this study a new receiver system has been proposed with the help of optical sources of which LO laser output signal is phase modulated and used to track the input signal. This optical phase tracking loop can be used to generate linear optical phase demodulation as shown in Fig.1.

To satisfy the need of highly stable laser sources, it is normal to think of using Nd:YAG or external cavity lasers. But these consume more power occupy larger space compared to DFB lasers. DFB lasers, while imposing stringent stabilization requirement on one hand, also have the advantage of potential opto-electronic integration [2]. So far, space based system DFB lasers would be right choice provided the rigidity of the stability condition can be enhanced. In this case stringent line width requirements and power of optical sources are prime importance, because the receiver sensitivity is highly dependent on these factors.

II. Theory

The basic operation of an optical phase-lock loop is illustrated by schematic Fig.1. This illustrates a loop in which the LO laser phase forms the output signal. The phase and frequency of tunable LO laser is controlled by filter output and the phase modulated LO signal modulates the input reference signal at optical mixer. Now, the optical mixer output can be expressed as

$$V_0(t) = [2\sqrt{P_S P_{LO}}\,\mathrm{Rr}\,.\,Sin(\varphi(t))]\; n(t) \qquad (1)$$

Where,

$$\varphi(t) = [\theta_S(t) - \theta_L(t) - \theta(t) - \gamma(t)] \qquad (2)$$

P_S : Power output of reference source,
P_{LO} : Phase modulator power output,
$\theta_S(t)$: Phase modulation due to phase noise of reference source,
$\theta_L(t)$: Phase modulation due to phase noise of DFB laser,
$\theta(t)$: Phase modulation of DFB laser by the phase detector output $V_0(t)$, as a result of instantaneous frequency control,
$\gamma(t)$: Phase modulation of DFB laser obtained as a result of application of the phase, detector output $V_0(t)$ to the phase modulator.
R is the responsitivity of the photo detector; r is load resistance of the photo detector and $n(t)$ is noise term due to shot noise. The spectral density of $n(t)$ is given by [1]:

$$S_n(f) = 4eR(P_S + P_{LO})r^2 \qquad (3)$$

'e' being electronic charge.
Further

$$\frac{d\theta}{dt} = K_V V_0(t) \qquad (4)$$

And $$\gamma(t) = K_p V_0(t) \qquad (5)$$

Where, K_{LO} and K_p is respectively the sensitivity of LO and optical phase modulator.
Using (1) to (5) the phase equation of the system is

$$\frac{d\varphi}{dt} = \Delta - F(s)e^{-s\tau}(K_{LO} + sK_p).(2\sqrt{P_S P_{LO}}\; Rr(Sin\varphi + n(t)) + \frac{d\theta_S}{dt} - \frac{d\theta_L}{dt} \qquad (6)$$

Where $F(s)$ loop filter transfer function, and $e^{-s\tau}$ indicates the effect of loop delay (τ).
Putting, $2K_{LO}Rr\sqrt{P_S P_{LO}} = \mathrm{K}$ and

$$\frac{K_p}{K_{LO}} = T_p \; and \; N(t) = \frac{n(t)}{Rr\sqrt{P_S P_{LO}}} \qquad (7)$$

Where T_p =Optical phase modulator sensitivity.
Equating eqn.(6) can be written as

$$\frac{d\varphi}{dt} = \Delta - KF(s)e^{-s\tau}(1 + sT_p).(Sin\varphi + n(t)) + \frac{d\theta_S}{dt} - \frac{d\theta_L}{dt}$$

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Referring eqn.(7) and eqn.(3), it is found that the spectral density of n(s) is given by

$$S_{SN}(f) = \frac{e(P_S + P_{LO})}{RP_S P_{LO}} \qquad (8a)$$

Now the phase of LO signal is expressed as

$$\varphi(s) = [\theta_S(s) - \theta_L(s)]\{1 - \frac{KF(s)e^{-s\tau}}{s+KG(s)e^{-s\tau}}\} - \frac{KF(s)e^{-s\tau}}{s+KG(s)e^{-s\tau}}\frac{n(s)}{A} \qquad (9)$$

Where $G(s) = (1 + sT_p)F(s) \qquad (9a)$

$$H(s) = \frac{KF(s)e^{-s\tau}}{s + KG(s)e^{-s\tau}} \quad and$$

$$1 - H(s) = \frac{s + KST_pF(s)e^{-s\tau}}{s + KG(s)e^{-s\tau}}$$

$$where\ s = j\omega = j2\pi f \qquad (10)$$

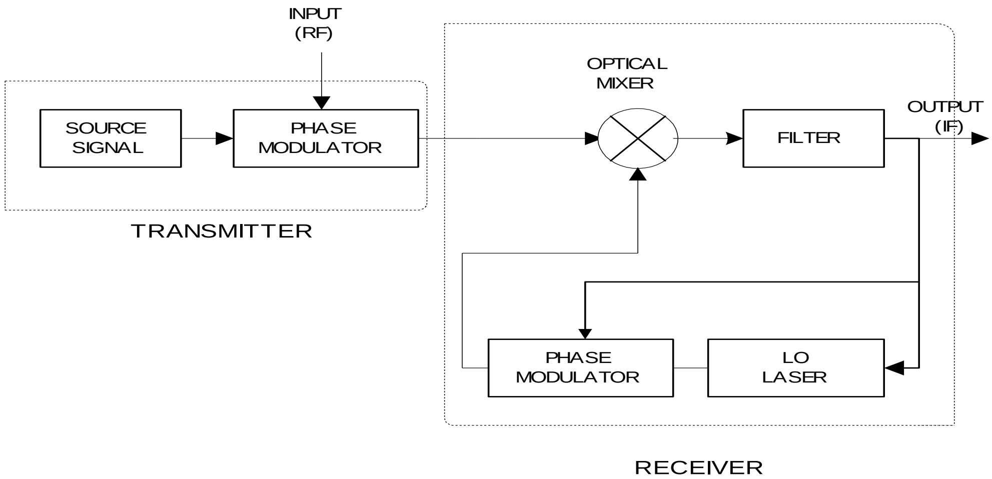

Fig.1. Concept schematic of novel phase-locked coherent optical phase demodulator.

III. The Phase Fluctuation Spectrum

The purpose of using the optical phase locked loop is to generate a microwave carrier by beating two lasers. The stringent phase requirement arises due to the fact that the transmitter power from a satellite is extremely expensive. This, in turn, requires that the receiver phase error should have a reasonably low value so as to keep the sensitivity degradation due to phase noise to a minimum. So, the power spectral density of the phase noise due to Gaussian White frequency noise of lasers, caused by the random spontaneous emission process in laser action, is given by [19, 20]:

$S_{PN}(f)$ = □ □ /□^{2}fad/Hz (11)

IV. Phase Error Variance

To obtain the expression for the phase error variance in the system shown in Fig.1, the loop equation (8) is linearised by putting $Sin(\varphi) \approx \varphi$. This is reasonable for all practical systems where the phase jitter is small. Thus, it is obtained as,

$$\varphi(s) = \frac{s(\theta_S(s) - \theta_L(s)) - KF(s)N(s)e^{-s\tau}(1 + sT_p)}{s + KF(s)(1 + sT_p)e^{-s\tau}} \qquad (12)$$

Putting

$$H(s) = \frac{KF(s)e^{-s\tau}}{s+KF(s)(1+sT_p)e^{-s\tau}} \qquad (13)$$

The phase error is written as

$$\varphi(s) = [\varphi(s)]_{PN} - [\varphi(s)]_{SN} \qquad (14a)$$

Where,

$$[\varphi(s)]_{PN} = [1 - H(s)][\theta_S(s) - (s)] \qquad (14b)$$

And $[\varphi(s)]_{SN} = H(s)N(s) \qquad (14c)$

Where $[\varphi(s)]_{PN}$ and $[\varphi(s)]_{SN}$ are the phase error due to the laser phase noise and shot noise respectively. Therefore, the mean square value of phase error due to shot noise and phase noise is obtained as

$$\sigma_{SN}^2 = \int_{-\infty}^{+\infty} S_{SN}(f)|H(f)|^2 df$$

$$and \qquad \sigma_{PN}^2 = \int_{-\infty}^{+\infty} S_{PN}(f)|1 - H(f)|^2 df \qquad (15)$$

Rewriting eqn.(15) and using (8a) & (11) we get,

$$\sigma_{SN}^2 = \frac{\omega_n}{2\pi PNB}\int_{-\infty}^{+\infty} |H(x)|^2 df$$

$$and \quad \sigma_{PN}^2 = \frac{2\delta v}{\omega_n}\int_{-\infty}^{+\infty} |1 - H(x)|^2 df \qquad (15a)$$

Where, ω_n = loop natural frequency

$x = \frac{\omega}{\omega_n}$

$As\ P_{LO} \gg P_S\ \ then\ S_{SN}(s) = \frac{e}{RP_S} = \frac{1}{2R_bPNB},$

$PNB = \frac{RP_S}{eR_b} = number\ of\ photons\ per\ bit,$

R_b = bit duration.

V. Stability of the Optical PLL

It is known that the introduction of a delay element in a phase locked loop modifies the behavior of the system in different ways. Out of these most serious one is the phenomena of false or spurious locking, in which the loop

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slips into false locking instead of locking to the instantaneous phase of the reference signal. Nonlinear analysis of this mode of operation of an optical PLL , when phase error is very large, is both time and space consuming. So, in this context, when phase error is small, it is worthy to look into the stability of linearised loop. The closed loop transfer function is considered,

$$H(s) = \frac{G(s)}{1+G(s)} \quad (16)$$

Where $G(s) = the\ open\ loop\ gain\ of\ PLL, is\ given\ by$

$$G(s) = \frac{KF(s)(1+sT_p)e^{-s\tau}}{s} \quad (17)$$

It is known that the system becomes unstable if the locus of G(j□) passes through or encloses the point (-1+j0) in the complex plane, the *x* and *y*-coordinates of the point respectively refer to the real and imaginary parts of G(j□). That is, for stability of the loop operation, the following conditions need to be satisfied [16, 17].

$$< G(j\omega) = -\pi \quad (18)$$

and $$|G(j\omega)| < 1 \quad (19)$$

Thus, referring eqn.(17), (18), (19) and taking filter transfer function as

$$F(s) = \frac{1+s\tau_2}{s\tau_1}$$

One finds that

$$tan^{-1}(\omega\tau_2) + tan^{-1}(\omega T_p) = \omega\tau \quad (20)$$

And

$$\frac{K^2(1+\omega^2\tau_2^2)(1+\omega^2T_p^2)}{\omega^4\tau_1^2} < 1 \quad (21)$$

$$\omega_n^2 = \frac{K}{\tau_1}; 2\xi = \omega_n\tau_2 \ \&$$

$$\xi = \frac{1}{\sqrt{2}} = loop\ damping\ constant \quad (21a)$$

Considering eqn.(20), (21) & (21a) one can easily show that

$$\frac{(1+2Z^2)\{1+Z^2(\omega_nT_p^2)\}}{Z^4} < 1 \quad (22)$$

$$tan^{-1}(\sqrt{2z}) + tan^{-1}(z\omega_nT_p) = z(\omega_n\tau) \quad (23)$$

Where $$z = \frac{\omega}{\omega_n} \quad (24)$$

For a standard second order loop with $T_p = 0$, the critical value of $\omega_n\tau$ for loop stability can be easily found by equating the left hand side of (24) to unity to find the value of z, which when substituted in (25) leads to the required value of $\omega_n\tau$.

Thus,

$$z^4 = 2z^2 + 1$$

i.e., $$z = \sqrt{1+\sqrt{2}} = 1.54$$

Using this value of z in (23), it is found that,

$$T_d = 0.736 \quad (25)$$

Now for the case when $T_p \neq 0$, we write (22) for the critical condition as

$$(1+2z^2)\left(1+z^2(T_p)^2\right) = z^4$$

i.e.,$$y^4 + y^2\left\{2+(T_p)^2\right\} - \left\{1-2(T_p)^2\right\} = 0 \quad (26)$$

Where $y = \frac{1}{z}$;

$$T_d = \omega_n\tau; \ T_p = \omega_nT_p \quad (27)$$

From (26) & (27) it is easy to calculate the value of z for different values of ω_nT_p, which on substitution in (23), leads to the required value of $\omega_n\tau$. This is illustrated in Table-1.

Table 1: Effect of LO phase modulation to Optical PLL stability

T_p	0	0.1	0.2	0.3	0.4	0.5	0.6
T_d	0.73	0.83	0.91	0.96	0.98	0.94	0.80

Thus, from above table it may be concluded that 14% increase of (□$_n$□) i.e., 0.98 compared to 0.73 is occurred due to LO phase modulation with normalized phase modulator sensitivity □$_p$ = 0.4. That is for same value of the loop natural frequency the loop can accommodate a larger value of delay element without hampering the stable operation of loop.

VI. Results and Discussions

The sensitivity of coherent optical phase lock demodulator is the prime important factor for coherent detection and the detection quality depends upon the function of different system components. Out of which, the optical sources, i.e. reference signal from the transmitter after long distance travel through optical wave guide is much weaker in strength and the LO laser with relatively high power modulates the input reference signals. The phase noise of the optical sources to the phase part of signal are generated because of spontaneous emission, though the stimulated emission is inevitable phenomena in Laser action and this undesirable emission causes the broadening of the spectral lines i.e. line-width. The state-of-art of optical receiver is the use of low line-width optical sources, but this enhances the system cost in practical purposes. Another important fact of detection process during which a quantum noise called shot noise is added to the signal to detection output. Also, the loop propagation delay has a vital role in the practical situation which degrades the stability and dynamic lock-in range of the loop.

Thus, a novel Optical PLL is designed for this demodulator in such a way that both, phase noise and shot noise are reduced to a large extent and stability boundary of the loop also increased. The shot noise reduction (SNR) is studied with LO phase modulation sensitivity for different values of PNB (ref. to Fig.2 & Fig.3). This shows shot noise variation with LO phase modulation sensitivity. Shot noise continuously decreases with phase modulation sensitivity. Effect of shot noise is high at low value of PNB, i.e., at low value of signal power. But the value is relatively low at high PNB value, i.e., at high power of optical source. The power requirements of optical sources has been improved by 2.79 dBm with additional phase modulation sensitivity , T_p = 0.4 at LO laser output as illustrated in Table-2.

The effect of phase noise variation is illustrated in Fig.4. The study shows that phase noise increases with the

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increase of lasers line-width. The results in table-3 indicates that line-width requirements for laser sources has been relaxed by 29.6% at phase modulation sensitivity, T_p = 0.4 without hampering the stable operation of the loop. The low line-width lasers are preferable for optical system for better performance, which is costly in practical purpose. So, the proposed system may accommodate higher line-width laser sources with same performance to make system cost-effective.

It is found that SNR decreases with PNB but PNR increases with line-width of optical sources. In this study, the phase modulation to LO signal provides extra feedback to the input signal that highly enhances the receiver sensitivity in terms of SNR, PNR and stability of loop.

Table 2: Improvement of laser power requirement at $□_p$ = 0.4, $□_n/R_b$=0.1.

$□_{SN}$	$□_p$	PNB	10.ln (PNB_1/PNB_2)
4.54^0	0	20.0 (PNB_1)	2.79
	0.4	10.5 (PNB_2)	
3.21^0	0	50.0 (PNB_1)	2.79
	0.4	26.3 (PNB_2)	

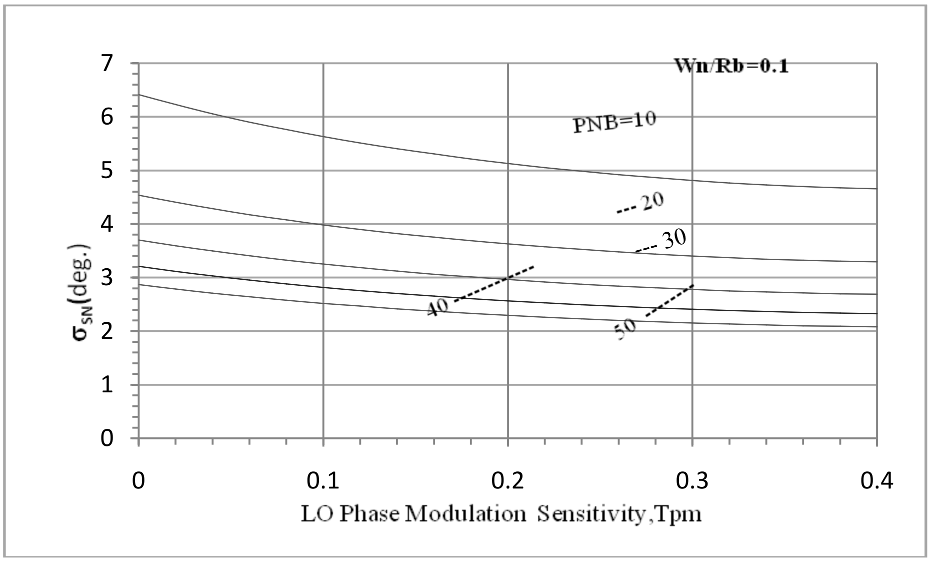

Fig.2. Variation of shot noise standard deviation with LO phase modulation sensitivity at Td = 0.4

Table 3: Improvement of stringent line-width requirement at $□_p$ = 0.4, $□_n/R_b$=0.1.

$□_{PN}$	$□_p$	□ □ □ MHz)	% of line-width requirement relaxed (□ □□□ □ □□□ x100
8.916^0	0	20.0 (□ □□□	29.6
	0.4	28.4□ □ □ □ □ □ □	
10.92^0	0	30.0	29.6
	0.4	42.6□ □ □ □ □ □ □	

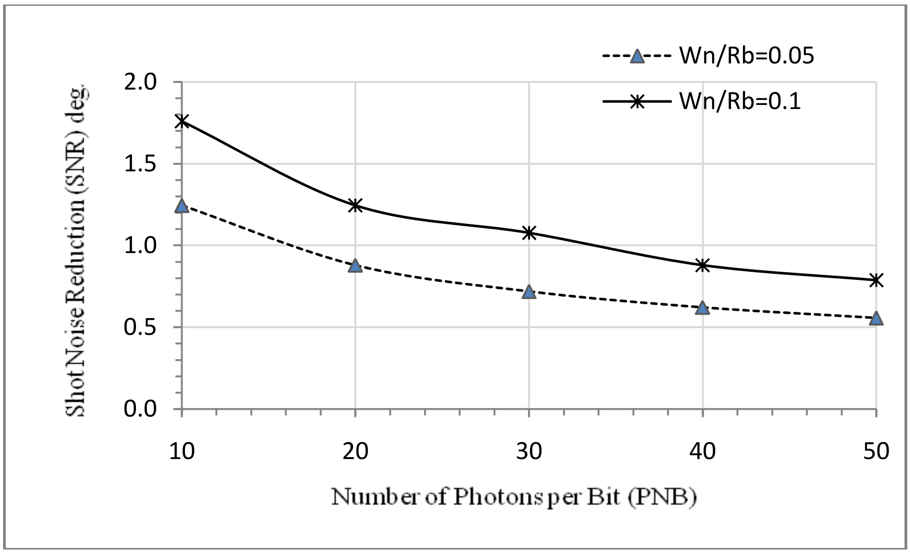

Fig.3. Shot Noise Reduction (SNR) with PNB at Td = 0.4 and Tp = 0.4.

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VII. Conclusion

The optical phase-lock demodulation technique has been utilized with the implementation of additional feedback to reference signal by phase modulation to LO signal. In this system, the receiver sensitivity is highly dependent on the costly optical sources and photo-detectors. Also, these components are responsible for the predominant noise sources i.e., phase noise and shot noise. The input reference signals after long distance travel through optical fibre is very weak in strength and for good reception, relatively high power LO signal is modulated with it. The inevitable quantum detection shot noise and random phase generation to the phase part of Laser broadens the spectral line-width. But the state-of-art of optical network is the use of low line-width with relatively high power laser. But it is cost-effective to hold these criteria. In view of these, a novel model is designed which relaxes the stringent line-width requirements up to 29.6% and power requirement improves up to 52.5% with normalized LO phase modulation sensitivity, T_p= 0.4 at T_d= 0.4. Thus, from above discussion it may be concluded that proposed system will provide better system performance than before used by other researchers and also use of DFB lasers *(line-width* $\sim 10\ to\ 50\ MHz$) will be promising effort in terms of cost-effective and system performance for future light wave networks.

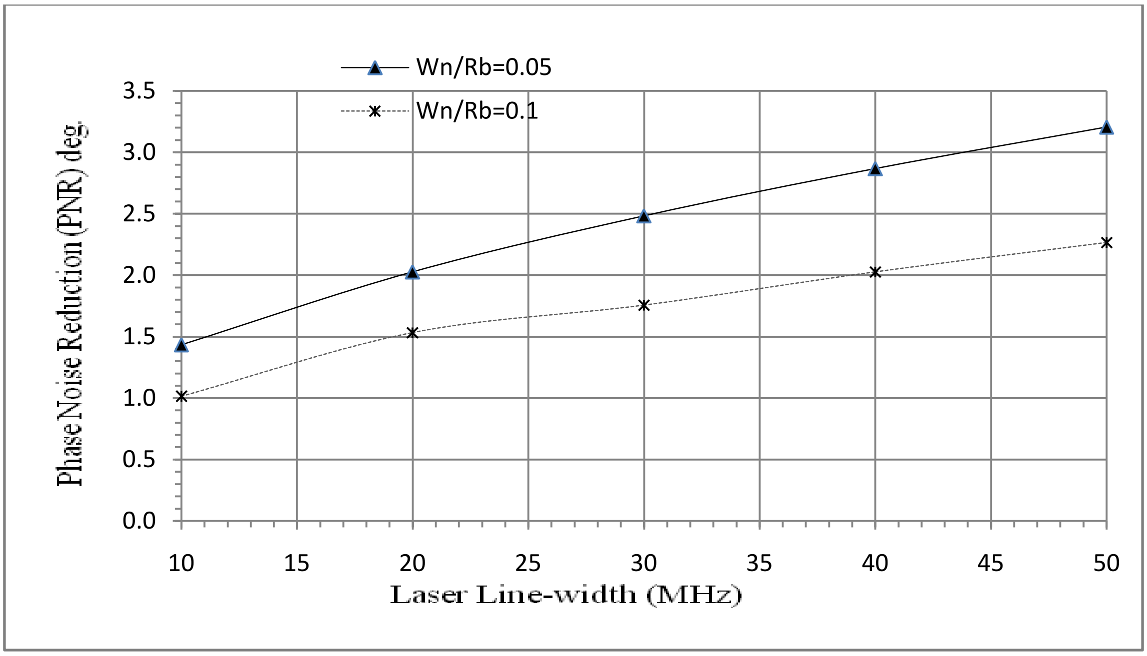

Fig.4. Phase Noise Reduction (PNR) with laser line-width at Td = 0.4 and Tp = 0.4

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APPENDIX

$$|H(x)|^2 = \frac{A^2 + B^2}{c^2 + D^2} \quad and \ |1 - H(x)|^2 = \frac{E^2 + F^2}{C^2 + D^2}$$

Where,

$$A = Cos(xT_d) - Sin(xT_d)$$

$$B = 2\xi x Cos(xT_d) - Sin(xT_d)$$

$$C = -x^2 + \left(1 - 2\xi T_{pm} x^2\right) Cos(xT_d) + x(T_{pm} + 2\xi) Sin(xT_d)$$

$$D = x(T_{pm} + 2\xi) Cos(xT_d) - \left(1 - 2\xi T_{pm} x^2\right) Sin(xT_d)$$

$$E = x - T_{pm}\{2\xi x Cos(xT_d) - Sin(xT_d)\}$$

$$F = T_{pm}\{Cos(xT_d) + 2\xi x Sin(xT_d)\}$$

AUTHOR'S PROFILE

Dr G. M. Helaluddin

Associate Professor in Physics, has been engaged in active research work in the field of optical communication and mobile communication. He has published number of papers in national and international journals. He is also the reviewer of a couple of journals. He has received S. K. Mitra memorial award from The Institute of Electronics and Telecommunication Engineers (IETE). He has delivered many lectures in different institutes in national and international seminars.