Analysis and Simulation of All-Optical Router for TDM-Based Optical Networks Using: NOLM

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Received on:23/7/2008
Accepted on:31/12/2008

Abstract

The work in this paper addresses all-optical routers for TDM optical networks. The core of the optical routers is the demultiplexer. In this paper all-optical router is analyzed and simulated. It is based on a TDM demultiplexer employing Nonlinear Optical Loop Mirror (NOLM). Expressions are derived for the transmission and reflection coefficients for the loop mirror employed in the demultiplexer. The effect of various system impairments, on the performance of the demultiplexer, such normal mode loss, control power, and losses, are addressed in details. Simulation results were carried out using MATLAB 6.5 software. The results indicate clearly that the demultiplexer should be designed precisely to achieve the required router performance.

Keywords: Nonlinear Optical Loop Mirror, Time Division Multiplexing, Nonreciprocity.

تحليل و محاكات الموجه البصري للشبكات البصرية المعتمدة على تقنية المتعدد المقسمة بالزمن: بستخدام حلقة المرآة البصرية الغير خطية (NOLM)

الخلاصة

في هذا البحث تم تحليل و محاكات موجه بصري و قد أعتمد على المتعـــدد المقـــسمة بـــالزمن TDM بتوظيف حلقة المرآة البصرية غير الخطية (NOLM). أن معادلات والعلاقات قد أشتقت لمعاملات الأرســـال و الأنعكاس للمرآة الحلقية المستخدمة في الموجه. أن التأثيرات لمختلف الأضرار بالنظام, على أداء المتعدد, مثـــل فقدان النمط الطبيعي, قدرة التحكم, و الخسارة, قد درست بالتفصيل. نتائج المحاكـــات قـــد عرضـــت بـــستخدام برنامج MATLAB 6.5. النتائج تدل بوضوح على ان المتعدد يجب ان يصمم بدقة لأحـــراز الأداء المطلـــوب للمتعدد.

1.Introduction

The Nonlinear Optical Loop Mirror (NOLM) demultiplexer is a promising configuration for achieving all-optical time division demultiplexing because of its high operating speed [1, 2]. Channel demultiplexing is realized by the phase difference between the clockwise (CW) and counter clockwise (CCW) signal pulses propagating within the fiber loop as in Fig. (1). Optical Time Division Multiplexing (OTDM) is an important way, which can greatly increase the bandwidth of a single wavelength channel. The key technology of OTDM systems includes ultrashort optical pulse generation; so by using NOLM we can demultiplex the received data depending on the nonlinearity of the loop mirror used. It has been shown that NOLM characteristics such as switching power, transmission and reflection coefficients are affected by the normal mode loss [3,4].

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We can form the NOLM by joining each of the two ends of an optical fiber to a four-port fiber coupler to make a Sagnac interferometer. Switching is accomplished by introduction of a relative phase shift between the two counter propagating signal pulses through cross-phase modulation induced by a control pulse [5]. A relative timing jitter between the control pulse and the signal pulse often occurs in practice, and the demultiplexer must allow for this by having a switching window that is significantly broader than the individual pulses.

2. Nonlinear Optical Loop Mirror demultiplexe

In this paper the transfer characteristics of the NOLM are analyzed for two cases

- Ideal case where the normal mode loss is balanced.
- Nonideal case where the normal mode loss is imbalance.

In both cases the effect of losses of the optical couplers is discussed. The configurations of the two-wavelength NOLM are shown in Fig. (1). The two (2X2) couplers are characterized by power coupling coefficients $g_x^s, g_{//}^s, g_x^c, g_{//}^c$ and $h_x^s, h_{//}^s, h_x^c, h_{//}^c$ which correspond to straight through (//) or cross-coupling (X) at the signal (λ_s) and control (λ_c) wavelengths, respectively.

The optimum configuration that maximize the switching efficiency and minimize the control power E_p is given by $g_x^s = g_{//}^s = 0.5, g_x^c = 1, g_{//}^c = 0, h_x^s = 0, h_{//}^s = 1, h_x^c = 1$ and $h_{//}^c = 0$ [3].

2.1 Ideal Case

The (2X2) coupler shown in Fig. (2) is considered. E_o is the input signal field amplitude at λ_s at port 1 of the coupler, E_1 is the reflection signal, and E_2 is the transmission signal. The output signal fields E_a and E_b corresponding to straight-through or cross-coupling, respectively, are given by as [2,4]

$$Ea = \frac{Eo(Ase^{ia} + Aae^{-ia})}{2} \qquad \text{....(1a)}$$

$$E_b = \frac{E_o(A_s e^{ia} - A_a e^{-ia})}{2} \qquad \text{.....(1b)}$$

where A_s and A_a represent the amplitude transmission of the symmetric and antisymmetric modes, respectively, and α is an unspecified phase shift. The power coupling coefficients $g_{//}$ and g_X can be expressed as [3]

$$g_{//} = \frac{|E_a|^2}{|E_o|^2} \qquad \text{..... (2a)}$$

$$g_X = \frac{|E_b|^2}{|E_o|^2} \qquad \text{.....(2b)}$$

Using Eqs. 1a and 1b, Eqs. 2a and 2b will take the following forms:

$$g_{//} = \left[\frac{A_s + A_a}{2}\right]^2 - A_a A_s \sin^2(a) \qquad \text{....(3a)}$$

$$g_x = \left[\frac{A_s - A_a}{2}\right]^2 + A_s A_a \sin^2(a) \qquad \text{.... (3b)}$$

By expanding Eqs. 1a and 1b, the two output fields E_a and E_b are given as

$$E_a = |E_a| e^{ia_a} \qquad \text{..... (4a)}$$

$$E_b = |E_b| e^{i a_b} \qquad \text{.....(4b)}$$

The relative phase difference is thus given by

$$d = \tan^{-1}\left[\frac{2 As Aa \sin(2a)}{(As^2 - Aa^2)}\right] \qquad \text{..... (5)}$$

When $As = Aa$ (ideal case) , then $d = \frac{p}{2}$ and the NOLM is said to be ideal.

the 2X2 coupler output fields take the form

$$Ea = Eo\sqrt{g_{//}} \qquad \text{... (6a)}$$

$$Eb = Eo\sqrt{g_x} e^{id} \qquad \text{.... (6b)}$$

The power reflection (R) and transmission (T) coefficients of the NOLM can be estimated with aid of Fig. (3). The output field at port 1 (reflection) and port 2 (transmission) are calculated as following

$$E_1 = E_a\sqrt{h^s_{//}} e^{-ia_{cw}} \sqrt{g^s_x} e^{jd} + E_b e^{-a_{ccw}} \sqrt{g^s_{//} h^s_{//}} \text{.... (7a)}$$

$$E_2 = E_a \sqrt{h^s_{//} g^s_{//}} e^{-ia_{cw}} + E_b e^{-a_{ccw}} \sqrt{h^s_{//} g^s_x} e^{id} \qquad \text{.....(7b)}$$

where a_{cw} and a_{ccw} are the phases integrated along the clockwise (cw) and counterclockwise (ccw) paths, respectively.

The normal mode loss imbalance parameter can be defined by the ratio [6]

$$X = \frac{1 - Aa^2}{1 - As^2} \qquad \text{.....(8)}$$

The 50/50 coupler has a coupling coefficient

$$g = g^s_x = g^s_{//} = \frac{As^2 + Aa^2}{4} \qquad \text{.....(9)}$$

and a coupling efficiency (overall transmission) [3]

$$s = \frac{As^2 + Aa^2}{2} \qquad \text{.....(10)}$$

The reflection and transmission coefficients of the NOLM are given by

$$R = \frac{|E_1|^2}{|E_2|^2} = 4 g^s_{//} g^s_x h^s_{//} \cos^2\left(\frac{\Delta a}{2}\right) \qquad \text{.....(11)}$$

$$T = \frac{|E_2|^2}{|E_0|^2} = h^s_{//}\left[(g^s_{//} + g^s_x)^2 - 4 g^s_x g^s_{//} \cos^2\left(\frac{\Delta a}{2}\right)\right] \qquad \text{.....(12)}$$

where $\Delta a = a_{cw} - a_{ccw}$ represents the phase difference between the cw and ccw signal waves, as induced by the control signal $E_c(t)$, coupled at port 3 of the NOLM

The phase difference (Δa) is a function of the control power and can be computed from [2,7]

$$\Delta a(\text{peak}) = \frac{4 p n_2 L_{eff}}{l_s A_{eff}} P_c^{in}(\text{peak}) \qquad \text{.....(13)}$$

where n_2 is the nonlinear Kerr index of the fused silica, L_{eff} is the effective interaction length, l_s is the wavelength of the input signal, and A_{eff} is the effective mode-field interaction area.

If an ideal 50/50 directional coupler is used for the loop mirror $a = p/4$, the effective switching power E_p^{eff} corresponding to the maximum transmission of the NOLM can be computed from Eqs.12 and13

$$E_p^{eff} = \frac{l_s A_{eff}}{4 p n_2 L_{eff}} \qquad \text{..... (14)}$$

Fig. (4) shows the transmission and reflection coefficients of a NOLM as a function of control power. The parameter values used in the simulation are given in

Table 1. These coefficients are plotted for three values of coupling efficiency (σ). One can notice that the maximum values of the transmission and reflection coefficients decreases with coupling efficiency. For example the maximum value of T an R is 1, 0.8 and 0.62 when σ=0, -0.5 and -1 dB, respectively.

2.2 Nonidial case

When $A_s \neq A_a$, then the NOLM is said to be nonideal. So Eq. 5 becomes [2]

$$d = \tan^{-1}\left[\frac{2\,AsAa\ \sin(2a)}{(As^2 - Aa^2)}\right] - z \qquad \text{.....(15)}$$

where x is the nonreciprocal phase shift between the symmetric and antisymmetric modes. The reflection coefficient does not depend on the nonreciprocal phase shift, which is due to the optical path reciprocity and therefore it should given by Eq. (11).The transmission coefficient becomes

$$T = h^s_{//}\left[(g^s_{//} + g^s_x)^2 - 4g^s_{//}g^s_x \cos^2\left(\frac{\Delta a}{2} + x\right)\right] \qquad \text{.....(16)}$$

Eq.13 can be rewritten as

$$E_p^{eff} = \frac{l_s A_{eff}}{4pn_2 L_{eff}}\left[1 + \frac{x}{p/2}\right] \qquad \text{..... (17)}$$

Equation17 reveals that in the case of unbalanced normal mode loss ($x \neq 0$), the control power required for complete NOLM switching is greater or lower, by a factor $\pm\frac{|x|}{p/2}$ than the generic value $E_p^{eff} = \frac{l_s A_{eff}}{4pn_2 L_{eff}}$. This result stems from the nonreciprocity of the loop mirror when operated in the transmission mode, i.e. the transmission depends on the value of E_p^{eff} instead of X .

Fig. (5) shows the transmission and reflection coefficients as a function of control power for different values of imbalance parameter X and efficiency σ. The reflection coefficient is not affected by the imbalance parameter, in contrast to the transmission coefficient. Fig. (5) also shows that in the presence of nonreciprocal phase shift the transmission and reflection coefficients [dashed line for $X = 4$, bold line for $X = 1$ (ideal), and normal line for $X = 0.2$] are shifted with respect to each other. This feature has two important consequences. First, in absence of control signal, the NOLM is no longer acting as a perfect mirror, since $T(P_c^{in} = 0) \neq 0$. In the case of X=0.2 or 4 , for instance, the transmission is $T(P_c^{in} = 0) \approx -18$ dB. The second consequence of nonreciprocity is the following; the maximum NOLM transmission (achieved for $P_c^{in}(peak) = P_p^{eff}(X)$) does not correspond to the NOLM minimum reflection $(R=0)$. In the case $X = 0.2$ or

4 for instance, the maximum achievable transmission $(T=0.63)$ corresponds to a reflection $R = -18$ dB. Minimum NOLM reflection $(R = 0)$ is obtained for $P_c^{in}(peak) = P_p^{eff}(X = 1) = P_p$, regardless of the value of X. In the case of constant control signal, therefore, it is possible to operate the NOLM at either maximum transmission $\left(P_c^{in}(peak) = P_p^{eff}(X)\right)$ or at minimum reflection $\left(P_c^{in}(peak) = P_p^{eff}(X=1) = P_p\right)$.

3. Demultiplexing

In time-demultiplexing applications of the NOLM, the control signal is a pulse [3], and the reflection and transmission coefficients are time-dependent. The control pulse has a Gaussian shape given by [8,9]

$$P_c^{in}(t) = P_{c\,(peak)}^{in} \exp\left[-4\log(2)\frac{(t-t_0)^2}{\Delta T^2}\right] \quad \ldots\ldots(18)$$

where ΔT is the control pulse width (Full Width at Half Maxima), t_o corresponds to the center of the switching window, and $P_{c\,(peak)}^{in}$ is the pulse peak power. The reflected and transmitted signals are defined as follows [8,10,11]

$$P_s^{ref}(t) = P_s^{in}(t) R(\Delta a(t)) \quad \ldots.(19a)$$

$$P_s^{trans}(t) = P_s^{in}(t) T(\Delta a(t)) \quad ..(19b)$$

where $R(\Delta a(t))$ and $T(\Delta a(t))$ are defined in Eqs. (11) and (12), respectively and $\Delta a(t) = f\left(p_c^{in}(t)\right)$ is computed from Eqs.13 and18. One can see that the maximum transmission occurs at t_o in which $\Delta a = \frac{p}{4}$.

Fig. (6a) shows the time-dependent NOLM reflection and transmission coefficients as defined by Eqs. (11) and (16), respectively. It is shown that the FWHM of the transmitted signal data should be within 10ps i.e. each signal needs 10ps to be demultiplexed. Fig. (7b) shows the transmission and reflection coefficients as a function of time when $E_p^{eff} = 83$ mW in which one can notice that the number of output signals increased in the specific time 20 ps, so by increasing the switching power the routing speed is increase too.

4. Effect of the Unspecified Phase Shift (α) on the NOLM Characteristics

The special case of α=π/4 rad yields 50/50 coupler. To calculate the dependence values of $g_{//}$ and g_x, on a we made use of Eqs. 3a, 3b, (9) and (10)

$$A_s = \sqrt{\frac{X + 2s - 1}{X + 1}} \quad \ldots..(20a)$$

$$A_a = \sqrt{\frac{2sX - X + 1}{X + 1}} \quad \ldots\ldots(20b)$$

Let $a = p/4 + \Delta$;

so Eqs.(3a) and (3b) can be rewritten as

$$g_{//} = \left[\frac{A_s + A_a}{2}\right]^2 - \frac{A_s A_a}{2}\left[1 + \sin(2\Delta)\right] \quad \ldots..(21a)$$

$$g_x = \left[\frac{A_s - A_a}{2}\right]^2 + \frac{A_a A_s}{2}\left[1 + \sin(2\Delta)\right] \quad \ldots.(21b)$$

When

$$\Delta = 0 \Rightarrow g_x = g_{//} = \frac{\left(A_a^2 + A_s^2\right)}{4} = g \quad \ldots.(22)$$

Note that when Δ is replaced by -Δ, then $g_{//}$ takes the expression of g_x and vice versa.

5. Effect of (Δ) on the Reflection and Transmission Coefficients

Consider the Ideal case X=1 (i.e. $x = 0$). Using Eqs. (11) and (12) and by setting $\Delta = 0$ then

$$R = 4g^2 \cos^2\left(\frac{\Delta a}{2}\right) \quad \ldots\ldots(23a)$$

and

$$T = h_{//}^{s} A^{4}\left[1-\cos\left(\frac{\Delta a}{2}\right)\right] \Rightarrow (50/50\ \text{coupler})$$

….(23b)

Consider the Nonideal case $X \neq 1$ (i.e. $x \neq 0$). Using Eqs. (12) and (15) yields
that T takes the form

$$T = h_{//}^{s} A^{4} \sin^{2}\left(\frac{\Delta a}{2}\right) \qquad \text{…..(23c)}$$

Fig. (8) shows the transmission and reflection coefficients as a function of Δ and assuming X=0.24, 1 and 4. The control power is set to 0 (i.e. off state). One can notice that the maximum transmission occur at Δ=0 rad.

The main conclusions to be drawn from Fig. (8) are

1. Ideal case

   For lossless coupler (σ=100%), operating with a =|π/4| rad (i.e., Δ=0), R_{max}=1 when T=0 and T_{max}=1 when R=0 and.
   When Δ=|22.5^0|, T=R for any value of σ, but each loss value has its relative value of T and R.
   For loosely coupler (σ≠100%), R_{max} and T_{max} are smaller than 1.

2. Nonideal case

   When X≠1, i.e. nonideal NOLM (X ≠0) and in the case of σ=100% (0dB), one can notice that the transmission and reflection coefficients are independent of X, since

$$A_a^{2} = \frac{2Xs - X + 1}{X + 1}$$

$$A_s^{2} = \frac{X + 2s - 1}{X + 1} \qquad \text{……(24a)}$$

(24b) so when σ=(0dB), Aa=As=1

For loosely coupler, i.e., σ >0dB the effect of X increases slightly.

In the case of σ=-1dB, the minimum transmission and reflection coefficients, occurring at Δ=0 rad and |π/4| rad, respectively, are affected by the value of the imbalance parameter (X).

However at the maximum values of transmission and reflection, occurring at Δ=|π/4| rad and 0 rad respectively, are independent of (X). This can be explained as follows

$$\Delta = 0,\ g_x = g_{//} = \frac{A_s^{2} + A_a^{2}}{4} \qquad \text{….. (25)}$$

$$A_a^{2} = \frac{0.558x + 1}{x + 1} \qquad \text{…….(26a)}$$

$$A_s^{2} = \frac{x + 0.558}{x + 1} \qquad \text{…… (26b)}$$

So for different values of X, $(g_x . g_{//}) = 0.3$ and R is independent of X at Δ=0 rad, while T is dependent on X since

$$T = 4 g_{//} g_x \left[\sin^{2}\left(\frac{\Delta a}{2} - x\right) + \frac{(A_s^{2} + A_a^{2})^{2}}{16 g_{//} g_x} - 1\right]$$

….(27)

At σ =1 dB, Δ=| π/4| rad

$$g_{//} = \frac{A_s^{2} + A_a^{2}}{4} - \frac{A_a A_s}{2} \qquad \text{…..(28a)}$$

$$g_x = \frac{A_s^{2} + A_a^{2}}{4} + \frac{A_a A_s}{2} \qquad \text{…….(28b)}$$

$$A_a^2 = \frac{0.558X+1}{X+1} \qquad \text{…..(29a)}$$

$$A_s^2 = \frac{X+0.558}{X+1} \qquad \text{….. (29b)}$$

So for different values of X, the magnitude ($g_{//}$,g_X) is variant according to X, i.e. R is independent of X and T is dependent of X.

2. As the efficiency decreases the effect of X starts to appear clearly since when σ =0dB, T and R are independent of X. So according to the design Δ≈0 low control sensitivity (maximum transmission production). Δ≠0 high control sensitivity.

6. Effect of Δ on the Coupling Ratio

we improved and expressed the percentage coupling ratio as

$R_{//}^{\%}$ =50-100sin(2Δ) …..(30a)

$R_x^{\%}$ =50+100sin(2Δ) …….(30b)

Where

$$\Delta = 0.5\sin^{-1}\left(\frac{50-R_{//}\%}{100}\right) = 0.5\sin^{-1}\left(\frac{R_x\%-50}{100}\right) \quad \text{…. (31)}$$

From Eqs. (30a) and (30b) one can find the results shown in Table (2).

7. Simulation of All-Optical Router

To demonstrate all-optical address recognition and single bit self- routing, a single node of all-optical time division multiplexed router is constructed from two demultiplexers; as shown in Fig. (9). The switching node consists of an all-optically controlled routing switch (demultiplexer2) to read the address of the packet, controller (Demultiplexer1), and a buffer. The controller optically sets the states of the routing switch (Demultiplexer2) in a switched or unswitched state. The optical buffer matches the delays of the input packet to the processing delay of the routing controller. When OTDM data signal enters the node, the clock, which is an orthogonal polarization signal, is separated from the optical packet using a polarization beam splitter (PS) and then used as the control signal of Demultiplexer1.

When OTDM data signal enters the node, the clock, which is an orthogonal polarization signal, is separated from the optical packet using a polarization beam splitter (PS) and then used as the control signal of Demultiplexer1.

A portion of the packet is split off and sent to Demultiplexer1 before entering the buffer. The Demultiplexer1 reads the packet

destination address bit, which is demultiplexed address bit and used as the optical routing control for the routing switch (Demultiplexer2). The optical packet, with a 10ps bit duration (e.g. 0.1 Tbit/s), is composed of a leading clock pulse, a 1bit header, and an empty payload. In a single bit routing scheme, the packet with address bit of value "1" are routed to output port 2, while packet with an address bit of value "0" are routed to output port 1. Thus photonic packets are self-routed through an all-optical switch without the need for optoelectronic conversion. The component count is reduced and the complexity of the routing architecture minimized.

Consider Fig. (10a) which shows the simulation results corresponding of the payload signals (three-bit packet). The control signal is coincident with the first signal (according to the design) which indicates the address bit. We make use of Eqs. (20a)- (20b)-(19b), with ΔT=10ps and t_o=10 ps.

It is assumed that each packet consists of three bits and the address bits selected by

the synchronized clock signals in which coincident with the address bits to be routed by Demultiplexer1 and then used as control for Demultiplexer2.

Figures (10 b and c) show, respectively, the output simulation of Demultiplexer1 as selected by the coincident clock signals, which indicates the address bits, and the routed payload information at port2.

8. Conclusions

1. Analytical expressions have been derived for the transmission and reflection coefficients for NOLM.

2.The maximum values of the transmission and reflection coefficients of the NOLM decreases with coupling efficiency.

3. The maximum transmission of the NOLM occurs at the maximum value of the unspecified phase difference a .

4.The reflection coefficient of the NOLM does not affected by the normal mode imbalance parameter.

5.The transmission and reflection coefficients of the NOLM independent of the normal mode imbalance parameter in the case of coupling efficiency=100%.

6.As the coupler's efficiency decreases the effects of non-reciprocity starts to appear clearly on the transmission and reflection coefficients.

7.The NOLM becomes more fast to demultiplex the signals within a specific time as the control power increases.

8.A new expression has been improved and expressed for the percentage coupling ratio.

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Table 1 Simulation parameters of the NOLM-based router.

Parameter	Value
Nonlinear Kerr index n_2	$3.2X10^{-20}$ m^2/W
Effective mode-field interaction area A_{eff}	35 μm^2
Effective fiber length L_{eff}	10 km
Signal wavelength λ_s	1.55 µm
Signal pulse width (FWHM)	10 ps
Data signal bit rate	50 Gbit/s
Data signal power	42 mW
Control pulse width (FWHM)	15 ps
Control pulse rate	25 Gbit/s
Unspecified phase shift a	$\pi/4$
Central time t_o	10 ps
Power coupling coefficient $h_{//}^{s}$	1
Pulse peak power $P_{c\,(peak)}^{in}$	42.3 mW

Table 2 Variation of the coupler ratio with Δ

Δ^o	$(R_{//}^{\%}/R_x^{\%})$
0	(50/50s)
1	(46.5/53.5)
2	(43/57)
3	(39.5/60.5)
4	(36/64)
5	(33/67)
-1	(53.5/46.5)
-2	(57/43)
-3	(60.5/39.5)
-4	(64/36)
-5	(67/33)

$(R_{//}^{\%}/R_x^{\%})$ coupler outputs ratio

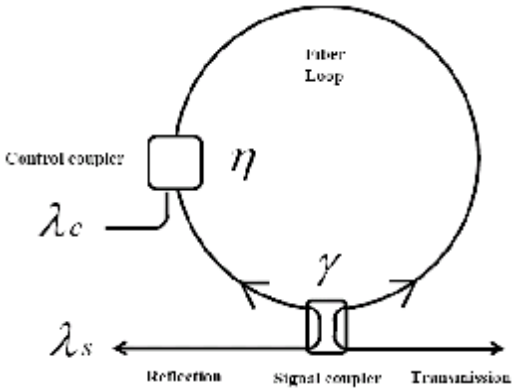


Figure (1) Configuration of two-wavelength NOLM with notations used in the text [3, 5].

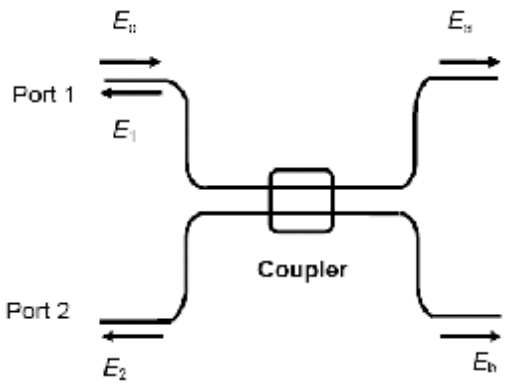


Figure (2) Basic 2X2 fiber coupler; the input/output electric field notation is as used in the text.

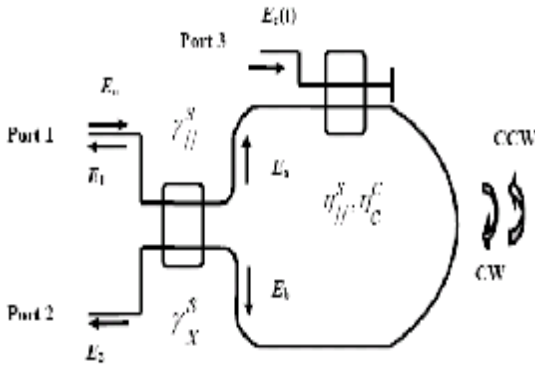


Figure (3) Two-wavelength NOLM; notation is as used in the text.

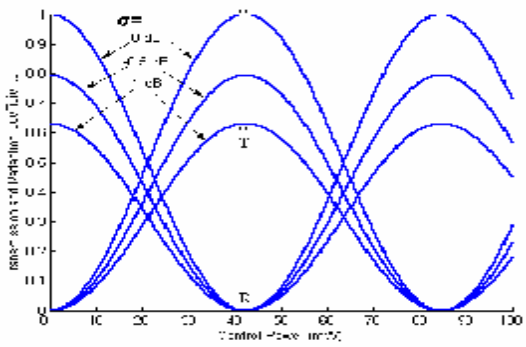
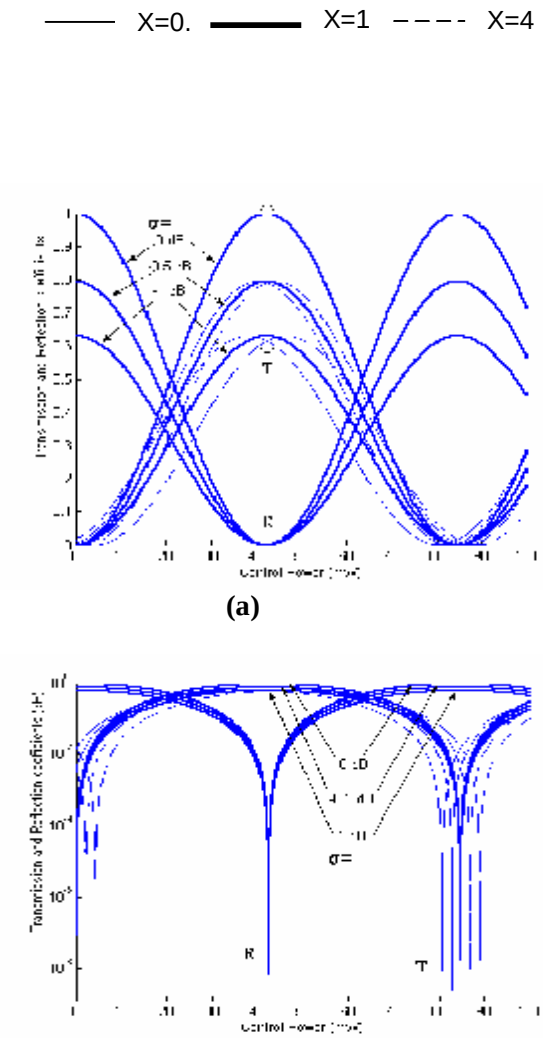


Figure (4) Transmission and reflection coefficients as a function of input control power for three values of efficiency (σ) 0, -0.5 and -1 dB.



(a)

(b)

Figure (5) Transmission and reflection coefficients as a function of input control power for three values of efficiency (σ) 0, -0.5 and -1 dB (a) Linear scale. (b) Decibel scale.

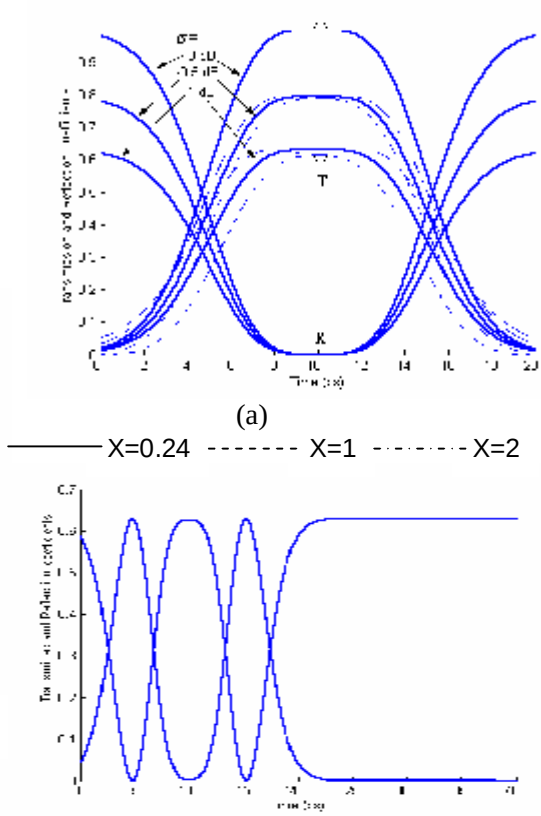
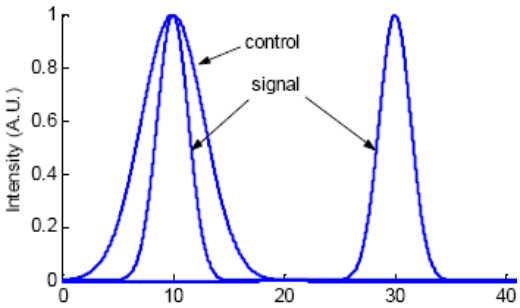
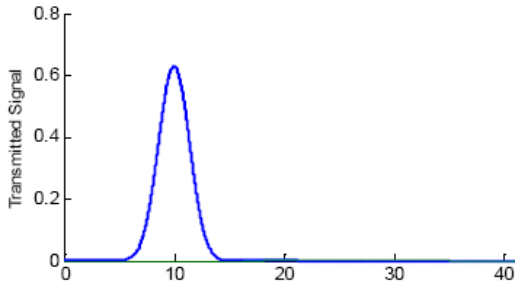


Figure (6) Illustrative waveforms.(a) Transmission and Reflection coefficients as a function of time for different values of efficiency σ and X. (b) Transmission and Reflection coefficients as a function of time X=1, σ=-1dB and E_p^{eff} =83 mW [3,7].

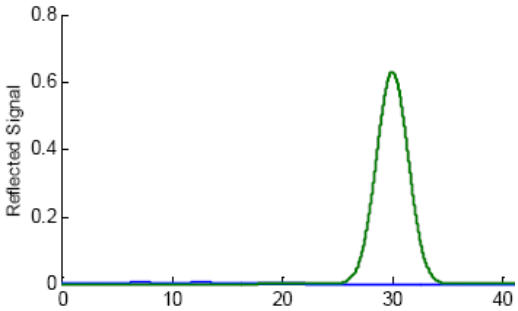


(a)

Figure (7) Illustrative waveforms (a) Control and input signals. (b) Transmitted signal. (c) Reflected signal of the NOLM, σ=-1 and X=1.

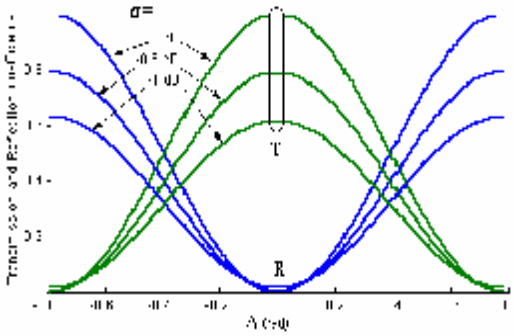


(b)

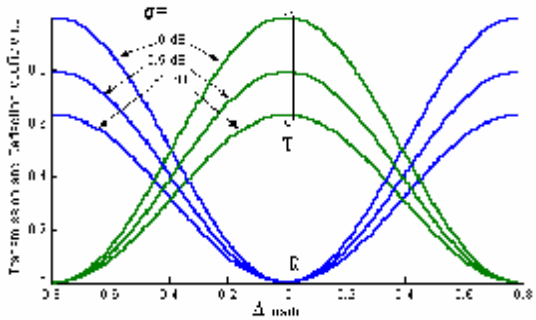


(c)

Figure (7) (Continued)

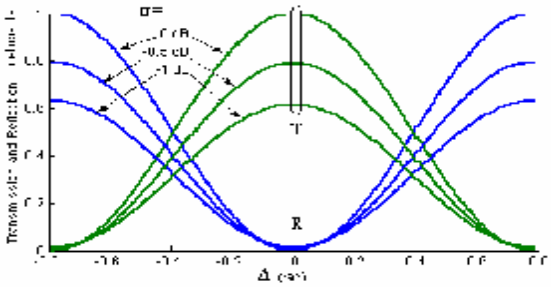


(a)



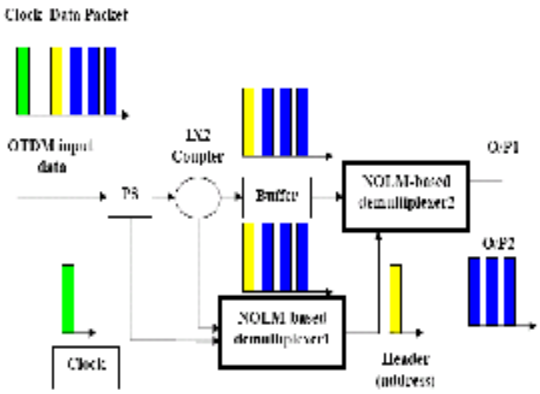
(b)

Figure (8) Transmission and Reflection coefficients as a function of unspecified phase shift (Δ) for three values of coupling efficiency (σ) and Pc=0 (mw). (a) X=0.24. (b) X=1. (c) X=4.



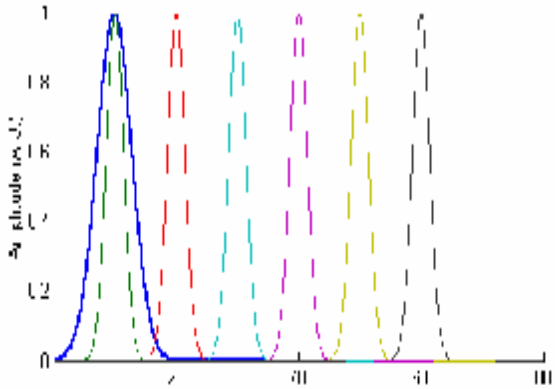
(c)

Figure (8) (continued)



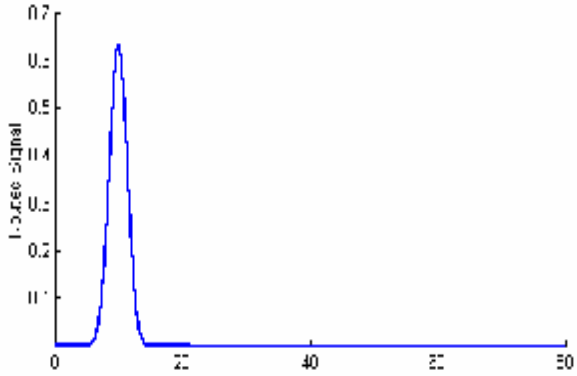
PS: Polarization splitter
O/P1: Output of port1
O/P2: Output of port2

Figure (9) Optical router (all waveforms are in time domain).

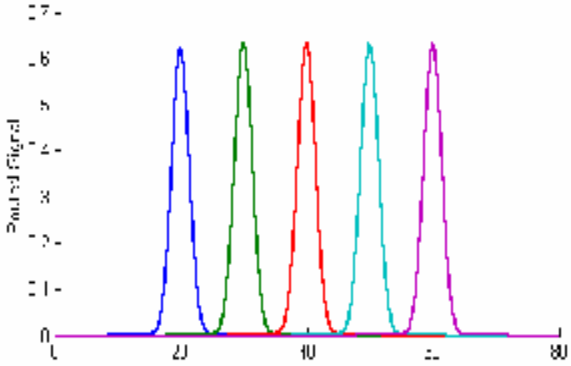


(a)

Figure (10) Illustrative waveforms. (a) Control and Payload signals. (b) Address bit as selected by the control signal. (c) Routed payload signals.



(b)



(c)

Time (ps)

Control Signal

Figure (10) (continued).