

# Programmable Coupler Ladder Based on Lithium Niobate Y-Junction Reflector

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**SUMMARY** This paper presents a proposal for a novel integrated tunable coupler device called programmable coupler ladder, based on Titanium diffused lithium niobate waveguide and Y-junction reflector. Unlike the traditional serial to parallel converter, the coupler ladder sorts the output bits in the time axis using a built-in delay waveguide. With a proper control signal it can perform signal processing at the bit level. It also can generate coherent multi-channel outputs with theoretically arbitrary amplitude and phase from continuous input light source. Its application in optical microwave beam forming is briefly described. The key component, built-in delay line based on Y-junction reflector, has been experimentally verified via a loop resonator structure. 1 dB loss is found for each Y-junction reflector, which enables a practical coupler ladder. The loop itself is also an important device for optical signal processing.

**key words:** lithium niobate, splitter, coupler ladder, loop resonator

## 1. Introduction

The 1 to  $N$  splitter is a key device in many optical signal processing applications such as label recognition of photonic packet switching networks, [1] data rate conversion for large-capacity storage networks, [2] all-optical register, [3] and optical RF beam forming [4]. Different splitters have been created using surface-emitting planar lightwave circuits, [1], [2] acousto-optic modulator, [3] or a fiber-based technique [4]. However, few of them can be easily re-programmed or fine-tuned to meet the dynamic variation of the networks.

In this paper, we propose a novel, compact, multi-functional signal-processing device composed of a group of tunable couplers on one single lithium niobate (LN) chip. The couplers are arranged in parallel, similar to the steps in a ladder, so that we refer to the device as a *coupler ladder*. The couplers transmit part of the light guided in a meandering waveguide, which acts as the built-in delay line. By applying voltage to electrodes at the coupler and along the meandering waveguide, the output amplitude and phase can be tuned for each output channel. Thus the programmable property of the coupler ladder can be achieved through an

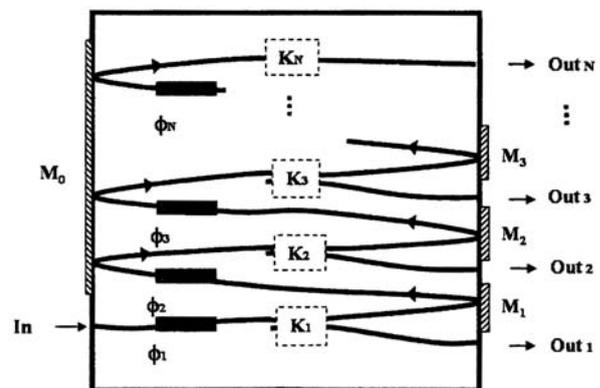
electric controlling circuit. Furthermore, the outputs channels are coherent with each other when a narrow band continuous wave (CW) laser is used as the source.

The meandering built-in delay line is identified as the key element in realizing the coupler ladder. Similar scheme has been reported to fold the long waveguide of the acousto-optic tunable filter so that the wafer can be downsized [5]. We extended the scheme to coupler ladder and experimentally verified it via a loop resonator structure, which consists of two Y-junction reflectors and is coupled with a straight-through waveguide. By measuring and analyzing the transmission of the loop, we have approximately measured the internal loss due to the Y-junction reflector.

The paper is organized as follows. First, the device structure of the coupler ladder is introduced. Second, the main functions and possible applications are briefly described. Third, the preliminary results of the loop resonator is presented, followed by a conclusion.

## 2. Structure of the Coupler Ladder

Figure 1 schematically depicts the structure of the programmable coupler ladder. Z-cut LN is chosen as the substrate material, due to its well-established fabrication technology. A meandering Titanium (Ti) diffused waveguide goes back and forth between the left and right facet of the LN substrate. Each turning point of the meandering wave-



**Fig. 1** A schematic diagram of the programmable coupler ladder. M: mirror; K: coupling coefficient;  $\phi$ : phase shifting electrode. There is actually no coupler for the final output channel.  $K_N$  is namely equal to 1 to represent an always-on state. The electrodes for controlling the coupling coefficient are not drawn explicitly.

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guide at the facet forms a Y-junction. The Y-junction consists of two waveguide branches merged together into one relatively wider multimode interference (MMI) branch. A metal or dielectric high reflection mirror is coated at the output of the MMI branch. With proper geometric design of the MMI section, the Y-junction can guide most of the incident light from one branch to the other, analogous to a mirror reflecting a light beam from one direction to another in the free space.

For each left-to-right section of the meandering waveguide, a coupling waveguide can be branched out from a certain point, so that a series of directional couplers can be made in parallel to each other from the bottom to the top. In Fig. 1,  $K_1, K_2, K_3 \dots K_N$  represent the couplers. The facet at the termination of each coupling waveguide is optically transmissive so as to couple light to the outside. The number of outputs,  $N$ , can be optimized subject to the limitation of the propagation loss.

The outputs, from 1 to  $N - 1$ , are equal to each other. The final one, the  $N$ th in Fig. 1, is a special one as it is the output of the meandering waveguide itself. There is actually no coupler for this channel.  $K_N$  is namely taken to be unity, representing an always-on state. This output can also be located at the opposite facet, depending on the applications.

Within the coupler ladder, the electrodes are used for two purposes: phase modulation and coupling coefficient modulation. Due to the excellent electro-optic property of LN, it is now routine to deposit the phase shifting electrodes along the meandering waveguide. In Fig. 1, we use  $\phi_1, \phi_2, \dots \phi_N$  to represent the phase shifting electrodes. Similarly, an electrically-controlled coupler or switch is also a well-established technology for Ti-diffused LN waveguide device, i.e., the coupling coefficients of  $K_1, K_2, K_3 \dots K_{N-1}$  can be tuned from 0 to 1 with proper applied voltage to the control electrodes [6], [7].

By tuning both the phase and the coupling coefficient, the output of every coupler can have arbitrary amplitude and phase modulations. The electro-optic response speed of LN is up to several tens of GHz, especially with traveling-wave type electrode [6]. Thus, high-speed tunability is achievable. A smart control circuit can be employed to generate suitable control signals for the electrodes. In this context, the device can function as a programmable coupler ladder.

### 3. The Basic Functions and Applications

The most straightforward function of the coupler ladder is to split the input signal into  $N$  channels, achieving serial-to-parallel conversion similar to the traditional  $1 \times N$  power splitter. However, this new device has a unique advantage over a traditional splitter; every output inherently has a relative delay to the other outputs. The relative delay time is determined by the length of the waveguide between adjacent couplers along the meandering waveguide.

Figure 2 depicts the simplified diagram for the pulse propagation and alignment.  $N$  is set to 4 for convenience. It is interesting to note that if the built-in delay time correlates

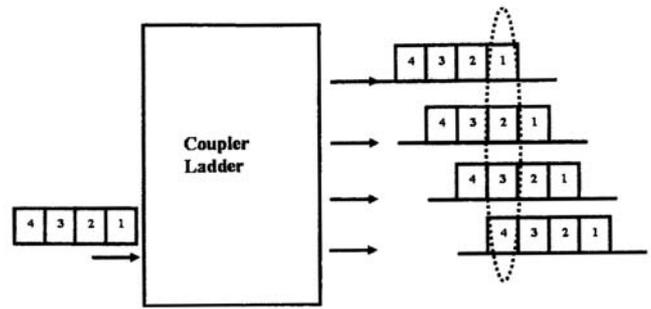


Fig. 2 Coupler ladder for pulse alignment after splitting.

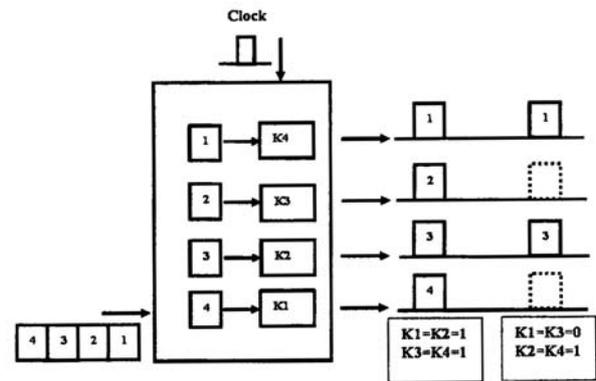


Fig. 3 Bit selection by different control words.

to the transmission bit rate then the output pulses will line up in the time axis. This is useful for signal processing applications such as label recognition in the packet switching networks

More splitting functions can be obtained with the help of an electrical control signal. As shown in Fig. 3, the input pulse can be sorted using the built-in delay. Assuming the control of the coupling coefficient  $K_i$  ( $i = 1, 2, 3, 4$ ) can be written under a synchronized clock, a different bit pattern can be acquired by applying different control words for  $K_i$ . For example, for  $K_1 = K_2 = K_3 = K_4 = 1$ , all the bits would be fanned out. For  $K_1 = K_3 = 0$  and  $K_2 = K_4 = 1$ , only pulse 1 and pulse 3 would be swept out. This enables the device to perform signal processing at the bit level. If only one channel is allowed to be coupled out, the device becomes a programmable router.

By reversing the input and output ports, the device is also able to operate as a parallel-to-serial convertor with the help of a synchronization clock. Due to the transmission characteristic of the directional coupler, an advantage of this device is that when one channel (say, the 2nd coupler) is open for the pulse to be coupled in, the undesired pulse flow coming from the upper channels (say, the 3rd and 4th) will be transmitted to the dummy end of the coupler of channel 2, so that the interference between the pulses will be avoided. With proper waveguide design, the light reaching the dummy end will radiate out to the substrate, without causing interference to the transmission waveguide. Figure 4 gives a simple illustration of this truncation phe-

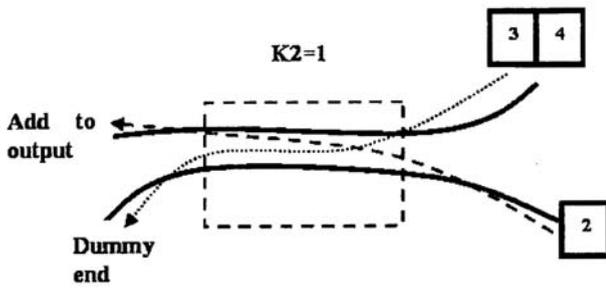


Fig. 4 Diagram of pulse adding and blocking.

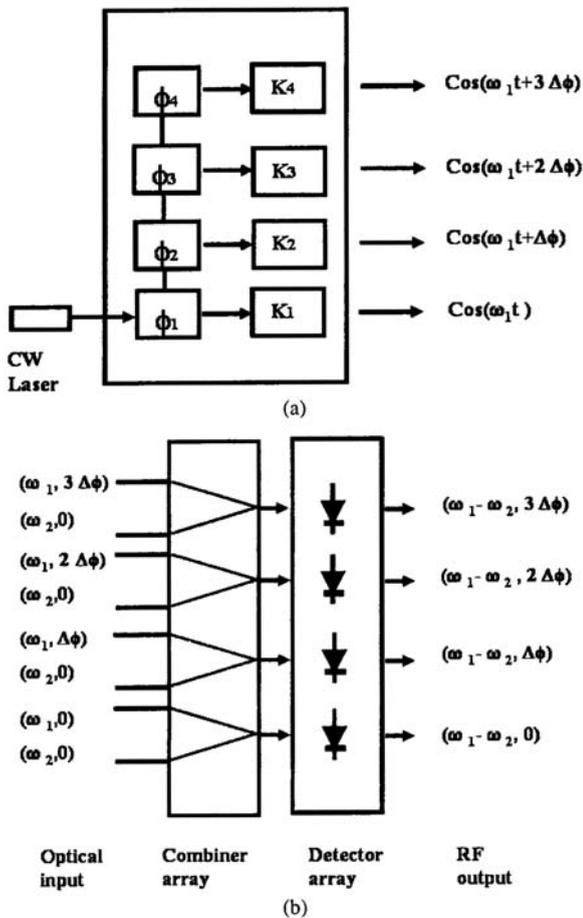


Fig. 5 (a) Coupler ladder functioning as an optical phased array. (b) Converting optical phased array to RF phased array.

nomenon. The truncation will not affect the normal pulses, which are still awaiting in the upper delay line.

Besides the applications to pulsed processing, the coupler ladder can also perform continuous lightwave processing by adjusting the amplitude and phase of each channel. Figure 5(a) illustrates how the coupler ladder generates the outputs with certain relations in phase and amplitude with each other. A narrow linewidth cw laser at  $\omega_1$  is used as the light source. For simplicity, we assume the output amplitudes are the same and are normalized to 1 by selecting proper values of  $K_i$ , so that only phases are under consideration. Since only the relative phase between channels is

important, we assume the phase output of first channel to be 0 as a reference. By tuning the phase shifter, the device generates a phase difference of  $\Delta\phi$  between every two adjacent channels.

A possible application for this coherent phased array is optical radio frequency (RF) beam forming. For this application a second coupler ladder at an output optical frequency of  $\omega_2$  and identical phases for every analogous channel is used. We can use a combiner array and a detector array to convert the signals from optical to RF domain. The output RF signals, which are the beat tone of  $\omega_1$  and  $\omega_2$ , will have the same phase difference  $\Delta\phi$  between every two adjacent channels. The RF generation process is briefly described in Fig. 5(b). The identical phase of  $\omega_2$  is set to be 0 since only the RF phase difference is of concern. The beat tone of two laser beams in the detector is governed by the equation below:

$$\begin{aligned} & [\cos(\omega_1 t + \Delta\phi) + \cos(\omega_2 t)]^2 \\ & \propto 2 \cos(\omega_1 t + \Delta\phi) \cos(\omega_2 t) \\ & \propto \cos[(\omega_1 - \omega_2)t + \Delta\phi] \end{aligned} \tag{1}$$

The DC terms and high order frequency terms are neglected in the derivation of (1). This method can thus be utilized to adjust the RF phased array signal by fine-tuning the optical phase.

A further thinking to improve the optical phase stability during the transmission is to alternate the mirrors in Fig. 1 with some bandpass filters, which reject  $\omega_1$  but allow  $\omega_2$  to pass through, so that  $\omega_2$  can be fed through  $M_0$  and mixed with  $\omega_1$  in the same coupler ladder chip. By this way, the combiner array in Fig. 5(b) is neglected and the phase scrambling can be reduced. The system will be more concise.

#### 4. The Loop Structure to Verify Y-Junction Reflector

The techniques of Ti-diffused waveguide fabrication, electro-optic phase shifting, and high speed coupling coefficient tuning have been studied and are quite well established [6], [7]. The key enabling technology for the coupler ladder is the delay line based on Y-junction reflector. Some of the preliminary results of the Y-junction reflector have been reported previously [8]. More detailed technical information about the junction is provided in the following.

A loop structure shown as Fig.6(a) was made at Sumitomo Osaka Cement Company. The device is composed of one straight-through waveguide coupled to a loop structure, which consists of two Y-junction reflectors connected to two waveguide branches. The metal-coated high reflection mirror can guide most of the light from one arm to the other arm. The coating, 120 nm thick Au with 6 nm thick Cr between the facet and Au, is applied only to the end facet of the Y-junction and not to the straight-through waveguide. For each end, a small piece of LN is glued to the top to support the coating of waveguide facet, which can be seen in the picture of Fig.6(b). A magnified top view to the waveguide

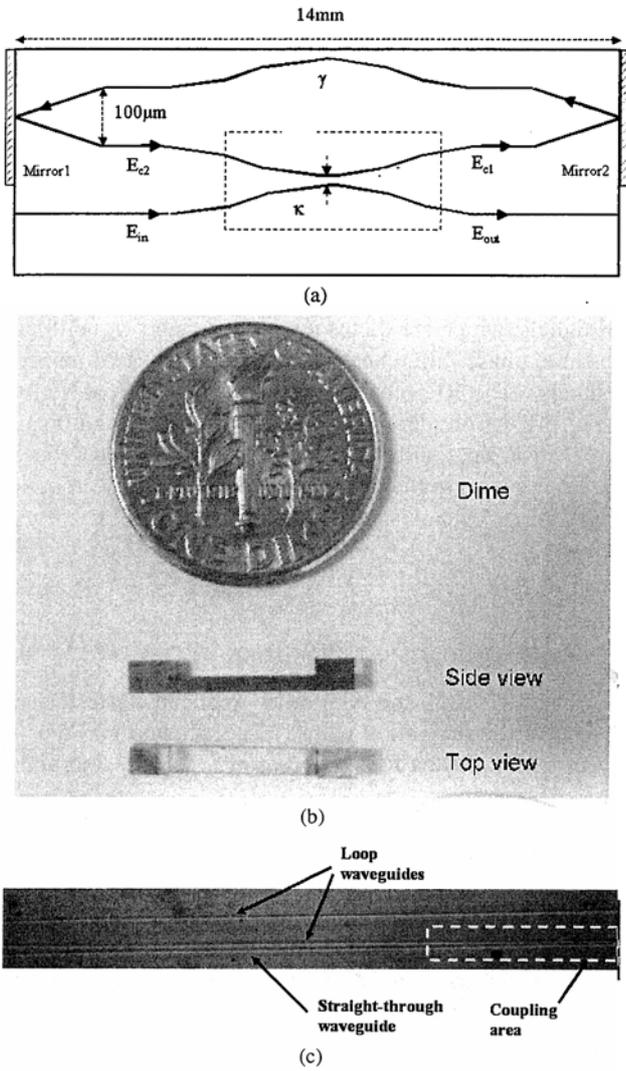


Fig. 6 (a) Structure of the loop resonator (not to scale). (b) Top and side views of the loop device. (c) Top view of part of the waveguide.

is given partly in Fig.6(c). The waveguide width is about  $6\mu\text{m}$ . The splitting angle of Y-junction is  $7^\circ$  and the MMI section length is  $56\mu\text{m}$ . These fine-tuned parameters make the Y-junction achieve low loss and high reflectivity.

Input light is coupled to the straight waveguide and then into the loop. The coupling coefficient is determined by 1) the effective modal index of the waveguide, 2) the length of the coupling region, and 3) the gap between the straight-through waveguide and the adjacent interconnecting waveguide of the loop. For our current devices, the gap varies from  $\sim 3.7$  to  $\sim 4.2\mu\text{m}$  to test different coupling coefficients; the length of the straight-through waveguide is  $\sim 14\text{mm}$ ; the separation between the upper and the lower arm of the Y-junction is around  $100\mu\text{m}$ . Therefore one round trip in the loop is about  $28\text{mm}$ . The chip shown in Fig.6(b) has an area of  $14\text{ mm} \times 1.8\text{ mm}$ .

To understand the behavior of the loop, the device is theoretically considered as one lossless coupler connected to the feedback waveguide [9], [10]. Define the loop round

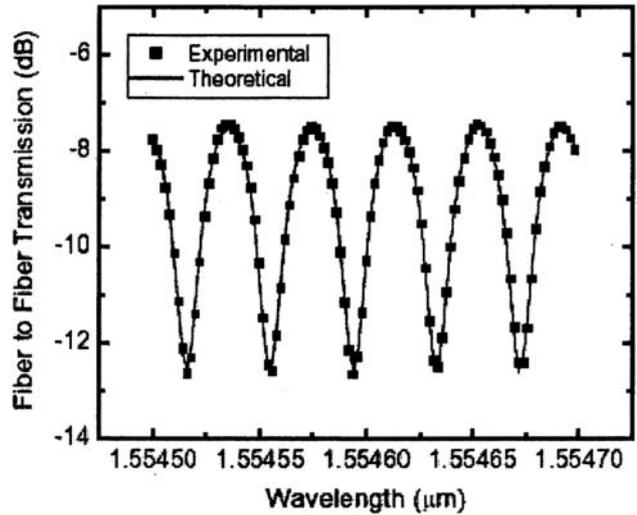


Fig. 7 Fiber-to-fiber transmission versus wavelength measurement (dots) of the sample and curve fitting (solid line).

trip phase as

$$\phi = \frac{2\pi}{\lambda} nL \tag{2}$$

where  $n$  is the waveguide refractive index,  $L$  is the effective waveguide length, and  $\lambda$  is the optical wavelength. The transfer function is given by

$$\frac{E_{out}}{E_{in}} = \frac{\rho - \gamma e^{-j\phi}}{1 - \rho \gamma e^{-j\phi}} \tag{3}$$

where  $E_{out}$  and  $E_{in}$  are the complex amplitudes of the electric fields for the input and output of the straight-through waveguide, respectively, as depicted in Fig.6(a).  $\rho$  is related to the power splitting ratio  $\kappa$  by  $\rho = \sqrt{1-\kappa}$ . The internal loss of one pass around the loop, which is given by  $-10 \log_{10} \gamma^2$  in dB, has been explicitly included in the transfer function.

The preliminary transmission measurements at different wavelengths, ranging from  $1.5545\mu\text{m}$  to  $1.5550\mu\text{m}$  by a tunable laser polarized in TM mode, are done to several devices with different coupling gaps. Figure 7 shows part of the transmission amplitude obtained from a device with  $4.1\mu\text{m}$  coupling gap. To fit the experiment results, the fiber-to-fiber transmission is given by

$$T = \Gamma \left| \frac{E_{out}}{E_{in}} \right|^2 \tag{4}$$

where  $\Gamma$  describes the loss caused by the coupling losses between the fiber and waveguide and also by the propagation loss of the straight-through waveguide.

The fitting result is shown in Table 1. The internal loss is mainly attributed to the Y-junction reflector and the waveguide propagation loss.

With  $\gamma=0.60$ , the internal loss is estimated at  $4.4\text{ dB}$  for the loop. It is hard to decouple the waveguide propagation loss (including the possible bending loss due to the imperfect coupler) and Y-junction reflection loss. If we assume

**Table1** Fitting parameters for the fiber-to-fiber transmission.

nL (μm)	ρ	γ	Γ
61740.7	0.248	0.60	0.32

an average waveguide propagation loss of 0.50dB/cm and a coupler bending loss of 0.50dB per bending [6], the total propagation loss due to the 2.8 cm long round trip loop waveguide is about 2.4 dB. The rest of the loss is due to the Y-junction reflection, which is 1.0 dB per Y-junction. The roughness of facet and coating quality are the main contributions to the reflection loss.

From the preliminary data obtained from the loop transmission, we note that the propagation loss can limit the channel number of the coupler ladder. When the total insertion loss is restricted to around 10 dB,  $N=4$  would be practical for the current situation. The loss can be reduced through the improvement of design and fabrication technique, or through the use of an optical pumped Erbium doped LN to compensate the loss with gain, which, of course, requires more research in the future [11].

**5. Conclusions**

In summary, we have proposed a new method to realize a multi-function programmable coupler ladder, based on the key technology of Y-junction reflection. Its applications to pulse transmission and continuous wave processing have been discussed. A loop structure is experimentally demonstrated to validate that the Y-junction can have a loss as low as 1 dB. It is possible to build a 4 channel coupler ladder with the insertion loss around 10 dB.

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