A Novel 2-D Programmable Photonic Time-Delay Device for Millimeter-Wave Signal Processing Applications

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Abstract— **We describe a novel programmable photonic true time-delay device that has the properties of low loss, inherent two dimensionality with a packing density exceeding 25 lines/cm^2, virtually infinite bandwidth, and is easy to manufacture. The delay resolution of the device is on the order of femtoseconds (microns in space) and the total delay exceeds one nanosecond (30 cm in space).**

FOR AIRBORNE and space-based phased array antennas [1] operating at mm-wave frequencies (20 GHz and above), two-dimensional beam-forming networks of high packing density, low loss, light weight, remoting capability, and immunity to electromagnetic interference are required. Photonic technology is naturally suited for such applications [2]–[5]. However, none of the proposed photonic beam forming networks to date meet all of the requirements specific to the mm-wave phased arrays, particularly the requirements of high operation frequency, high packing density, and fine delay resolution (the minimum step of delay change). The delay resolution is important and must be fine enough (much less than the wavelength of the signal) to ensure that the angular resolution of the beam scanning is sufficient.

The true-time-delay beam forming networks [2]–[4] based on acousto-optic modulators are limited by low operation frequency (below 10 GHz) and narrow bandwidth (below 100 MHz). The path-switching time-delay devices based on guided wave optics [6]–[8] are complicated and are characterized by high loss, high cost, poor delay resolution, and one-dimensional geometry. The free-space path-switching time-delay device proposed by Riza [9], [10] is 2-D with high packing density, and operates at high frequency with sufficient total delay. However, the optical path delay resolution of the device is limited by the size of the vertical dimension of the 2-D delay array and is inadequate for signals with a wavelength of only a few millimeters.

In this paper we describe a novel photonic true time-delay device that is suitable for mm-wave phased arrays. This programmable device is inherently two dimensional, and has the properties of high packing density, low loss, easy fabrication, and virtually infinite bandwidth. The delay resolution of the device is sufficiently fine for accurate beam steering, and the total delay is adequately large to cover desired scanning angles. This device can also be simplified to a phase-shifter beam-former for phased arrays of narrow bandwidth, where true time-delay is not necessary. The same device is also suitable for photonic mm-wave transversal (adaptive) filters [11], [12].

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Figure 1(a) depicts the proposed index switching true time-delay device. The delay unit consists of birefringent crystal segments. Each segment is cut along the principal axes of the crystal with the light beam propagating along the X (or Y axis). The light beam is polarized either in the Z direction or in the Y (or X) direction (the two principal directions of the crystal). The Y (or X) polarized beam experiences a refractive index of n_0 and the Z polarized beam experiences a refractive index of n_e. A polarization rotator is sandwiched between each pair of segments to change the beam's polarization states by 90 degrees, either from Y (or X) to Z or from Z to Y (or X). The polarization rotator can be a liquid crystal, a magneto-optic or an electro-optic element. It is evident from Fig. 1(a) that the time-delay of the beam can easily be altered by changing the beam's polarization in each segment. We call this method index-switching technique.

To minimize the number of polarization rotators in the device [13], the lengths of the crystal segments increase successively by a factor of 2, as shown in Fig. 1(a). The relative optical path delay Δl between the two polarization states in the smallest segment of length l (the least significant bit) is

$$\Delta l = (n_e - n_0)l. \quad (1)$$

Let M be the total number of crystal segments (or bits), then the maximum value of the optical path delay generated is:

$$\Delta L_{\max} = (2^0 + 2^1 + 2^2 + \cdots 2^{M-1})\Delta l = (2^M - 1)\Delta l \quad (2)$$

By properly adjusting the polarization state of the light beam in each segment, any time-delay in the range from $\Delta l/c$ to $\Delta L_{\max}/c$ can be obtained with a resolution (or delay increment) of $\Delta l/c$. In (1) and (2), we have neglected the delay variation in the polarization rotator when the polarization is rotated. Based on the thickness ($\sim$10 μm) and the birefringence (about 0.1) of the liquid crystals, the corresponding delay is on the order of a few femtoseconds (microns in space).

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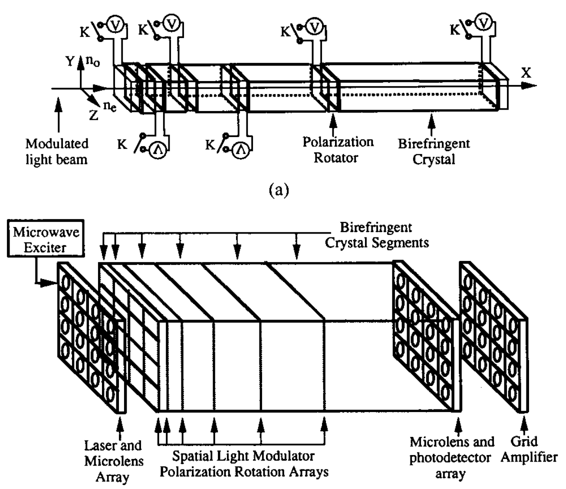

(b)

Fig. 1. (a) Illustration of an index-switching true time-delay device. Optical path delay of the modulated light beam is varied by rotating the polarization of the beam so that it experiences either n_0 or n_e of the refractive index in each crystal segment. To compress the number of polarization rotators, binary delay variation is preferred and depicted. (b) Many delay lines are densely packed to form a 2-D time-delay beam forming device for a phased array antenna.

TABLE I
POTENTIAL BIREFRINGENT MATERIALS FOR THE INDEX-SWITCHING DELAY DEVICE AND THEIR BIREFRINGENCE

	n_e	n_o	$n_e - n_o$	$\Delta\tau$/mm
Rutile (TiO_3) [15] (λ = 589.3 nm)	2.903	2.616	0.287	0.96 ps/mm
Ag_3AsS_3 [16] (λ = 633 nm)	2.739	3.019	0.28	0.93 ps/mm
Sodium Nitrate [15] (λ = 589.3 nm)	1.3369	1.5854	-0.2485	0.83 ps/mm
Calcite [15] (λ = 589.3 nm)	1.4864	1.6584	-0.172	0.57 ps /mm
$LiNbO_3$ [16] (λ = 633 nm)	2.2	2.286	-0.086	0.29 ps /mm
$LiTaO_3$ [16] (λ = 633 nm)	2.18	2.176	0.04	0.13 ps /mm
Quartz [15] (λ = 589.3 nm)	1.5534	1.5443	0.0091	0.03 ps /mm
PM Fiber (λ = 1300 nm)			~ 6 x 10^{-4}	~2 fs /mm

Table I lists the refractive indices and the corresponding delay rates (time-delay per unit length) of potential birefringent materials for fabricating the proposed delay lines. Note that different crystals may be used together to construct a delay line: a crystal with small birefringence can be used to make segments of small delays (less significant bits) and a crystal with large birefringence can be used to make segments of large delays (more significant bits).

The maximum delay [1] $\Delta L_{\max}$ required of a beam forming network of a phased array antenna with $N \times N$ elements is

$$\Delta L_{\max} = (N-1)d_{\max}\sin|\theta_{\max}| = \frac{(N-1)\lambda \cdot \sin|\theta_{\max}|}{(1+\sin|\theta_{\max}|)} \quad (3)$$

TABLE II
REQUIRED MAXIMUM DELAY AND DELAY RESOLUTION FOR A PHASED ARRAY OF 64 × 64 ELEMENTS, AN OPERATION FREQUENCY OF 40 GHz (0.75 CM), AND A BEAM SCANNING ANGLE RESOLUTION OF 1° (THE REQUIREMENTS OF CORRESPONDING CRYSTAL LENGTH AND TOTAL NUMBER OF BITS ARE ALSO LISTED)

	$\theta_{max} = 5°$	$\theta_{max} = 10°$	$\theta_{max} = 30°$	$\theta_{max} = 60°$
ΔL_{max}	3.78 cm or 5.04 λ	7 cm or 9.33 λ	15.75 cm or 21 λ	21.93 cm or 29.24 λ
L_{max} (Rutile)	13.48 cm	24.4 cm	55 cm	76.4 cm
Δl	0.12 mm	0.11 mm	0.0756 mm	0.035 mm
l ($LiNbO_3$)	1.4 mm	1.3 mm	0.87 mm	0.41 mm
M No. of bits	7	8	11	12

where $\theta_{\max}$ is the maximum beam scanning angle, λ is the wavelength of the carrier (microwave) signal of the phased array, and $d_{\max} \equiv \lambda/(1+\sin|\theta_{\max}|)$ is the maximum array spacing [1] allowed before higher order diffraction degrade the antenna gain.

The path difference l_d between two adjacent elements is $l_d = d_{\max}\sin\theta$, where θ is the beam pointing angle from the array normal. Taking the derivative of this equation, we obtain the delay resolution Δl required for an angular beam scanning resolution of $\Delta\theta$ to be

$$\Delta l = \frac{\lambda \cdot \cos\theta_{\max}\Delta\theta}{(1+\sin|\theta_{\max}|)}. \quad (4)$$

Table II lists the values of required maximum delay $\Delta L_{\max}$ and delay resolution Δl for a phased array with $\lambda = 0.75$ cm (40 GHz), $N = 64$, and $\Delta\theta = 1°$. The corresponding crystal lengths for the maximum and the minimum delays are also listed. For example, for the case of $\theta_{\max} = 30°$ $LiNbO_3$ crystal of length 0.87 mm can be used to make the segment of the smallest delay of 76.5 μm and the Rutile crystal of the total length of about 55 cm can be used to make other larger delay segments that have a total delay of 15.75 cm. In the table, the number of bits M is calculated using $M = \log_2(1+\Delta L_{\max}/\Delta l)$.

The same concept can also used to make phase shifters for phased array antennas with narrow bandwidth where true time-delay is not necessary. For example, an 8 GHz (X-band) carrier has a wavelength of 3.75 cm. To obtain a total phase shift of 2\pi for such a carrier, a total length of only 13 cm of Rutile crystal per channel is required. For a Ka band carrier of wavelength of 0.75 cm (40 GHz), only 2.6 cm Rutile crystal per channel is required.

It should be noted that Rutile has excellent optical and physical properties: [14] it is transparent to light from 500 nm to 5 μm and its birefringence $(n_e - n_0)$ remains almost unchanged from 430 nm to 4 μm. It has a thermal expansion coefficient few times less than glass and a solubility in water less than 0.001.

Several delay lines of the design described above can be densely packed in 2 dimensions to form a compact beam

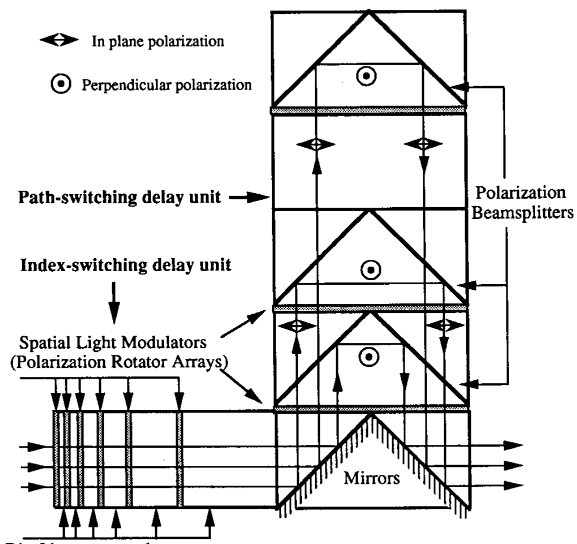

Fig. 2. Cascading an index-switching delay unit with a path-switching delay unit. In the path-switching unit, the ray polarized in the plane of the paper will pass polarization beam splitters (PBS) unaffected and the ray polarized perpendicular to the plane will be reflected by the PBS. The polarization rotators in each ray path control the polarization states of the ray and thus its optical paths. The distances between PBS blocks increase successively by a factor of two to make the delay changes binary.

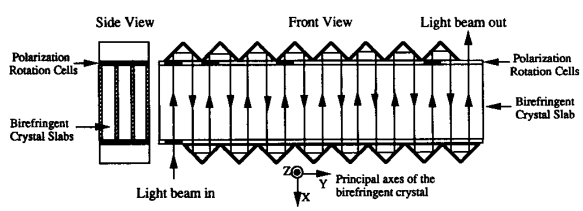

Fig. 3. The zig-zag construction of the index-switching delay device. The polarization state of the light beam can be switched between Y and Z directions by the 90° polarization rotation cells, and the beam will experience n_0 and n_e accordingly. The spacing between the polarization rotation cells increases successively by a factor of two to make the delay line binary. Many such delays (three are shown) can be stacked together to form a 1-D array.

forming network, as shown in Fig. 1(b). The spatial light modulators are used to control the polarization in each segment of each channel. For 2 mm channel spacing, the packing density of the device is 25/cm^2. Such a channel spacing is easily attainable in practice, considering that a 1.4-mm diameter Gaussian beam with 1-μm wavelength has a Rayleigh range of 1.54 m.

The index-switching delay elements may be cascaded with a free-space path-switching delay device of Riza [9], as shown in Fig. 2. The total delay is 8 bits. The first six bits have smaller delay increments and use index-switching technique to construct. The last two bits have large delay increments and therefore use path-switching technique. The total length of the crystal segments per channel is now reduced to a few centimeters. Note that the architecture of the path-switching delay unit depicted here is dramatically different from those previously published [9] and is much more compact and simple to fabricate.

The index-switching time-delay unit may also be constructed using a single slab of a crystal, as shown in Fig. 3. Compared with the linear construction of Fig. 1, the zig-zag construction uses less crystal. However, it is inherently one-dimensional and thus has a lower packing density than that of the linear construction.

In summary, we have described a novel programmable photonic true time-delay device that has the properties of high packing density, low loss, easy fabrication, and virtually infinite bandwidth. Such a device is ideal for a beam forming network of a phased array operating at Ka band ($\sim$ 40 GHz) and higher frequencies and for millimeter wave transversal filters.

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