NONCOLLINEAR SECOND-HARMONIC-GENERATION-BASED ULTRAFAST OPTICAL SIGNAL PROCESSING FOR OPTICAL DIGITAL COMPUTING

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The use of second harmonic generation (SHG) effect for ultrafast digital optical computing is proposed. A number of SHG-based optical architectures are presented. Experimental results of an ultrafast optical digital multiplication are included.

1. Introduction

Large scale parallelism and ultrafast switching speed are the two major attractions for the use of digital optical computation [1]. Acousto-optical (A-O) and electro-optical (E-O) parallel processors have been designed [1–3]. Although these hybrid processors can readily be used to perform various digital computations, their processing speeds are not sufficient for high speed real-time applications. In this letter, using both the parallel processing property and ultrafast switching advantages of optics, the noncollinear optical second harmonic generation (SHG) effect for digital optical array processing is demonstrated. The advantages of a SHG based optical array processing are discussed. A number of optical computational examples together with some preliminary experimental results are presented.

When two identical optical beams pass through a SHG crystal, depending on the beam propagation geometry for a 90° phase-matching, a frequency-doubled (second-harmonic or SH) output signal can be generated [4,5]. The input and the SH signals are the so-called ordinary and extraordinary polarized beams, respectively. The SH signal emerges with an angle that bisects the input beam intersection angle ϕ. When pulsed inputs are used, the SH signal spatial profile represents the input temporal autocorrelation function. Since the input and output frequencies are well separated and the phase-matching condition acts as an angular filter, noncollinear SHG has widely been used as a background-free detection method for measuring temporal information down to 8 fs [6]. However, despite of this speed advantage due to purely electronic nonlinearity, the use of SHG for ultrafast digital processing and computing has not yet been explored.

2. SHG-based optical AND gate array

From a logic point of view, a SHG device can be viewed as an optical AND gate. Using either frequency or polarization filtering, the SH output signal can easily be isolated. Furthermore, because of its angular symmetry, the two emerging inputs can be used, without the use of any additional optical components, as the inputs to the next-stage SHF AND gates. Thus, using a parallel input format, a lattice type SHG AND gate array can be formed. In fig. 1(a), a four AND gate noncollinear SHG-based logic network is shown. Here, D_x (D_y) and ϕ denote the input signal channel spacings for input X (Y) and input crossing angle inside the crystal, respectively. The inputs (SH outputs) are marked with solid (dashed) lines, respectively. The four AND operations are performed inside a single SHG crystal. To insure that at each AND gate the pulsed signals overlap, an input oblique time wavefront angle

$$\theta=\sin^{-1}[n_o(\lambda)\sin(\phi/2)] \quad (1)$$

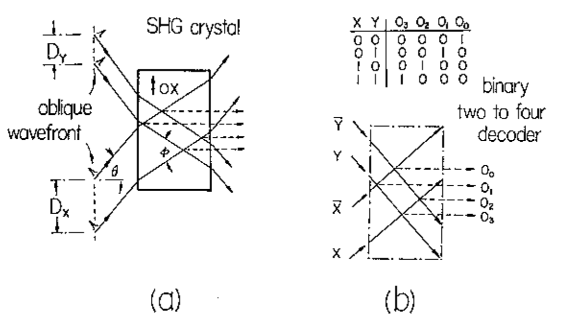

Fig. 1. (a) A nonlinear SHG-based logic network. Solid (dashed) lines represent the main (SH) signal beams. OX, crystal optic axis; ϕ, phase-matched input beam crossing angle inside the crystal; $D_{x(y)}$, input bit spacing for channels $x(y)$; θ, input array temporal oblique wavefront angle. (b) Binary two-to-four decoder truth table and its logic connection. The availability of both logic and their complement is assumed.

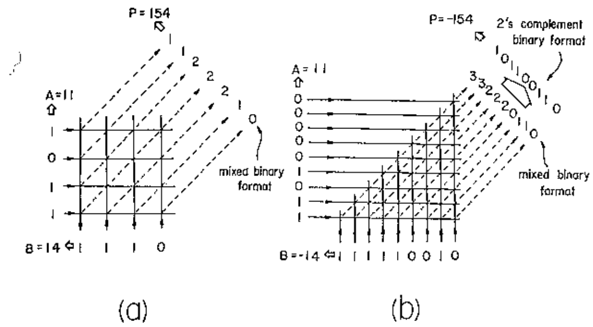

Fig. 2. Schematic of SHG-based digital optical multiplication networks. (a) A binary unsigned multiplication preprocessing network with spatially encoded binary inputs. The optical numbers enters from the left and bottom of the processor. The SH output signal represent the MBR multiplication result. (b) A TCB multiplication preprocessor.

is needed. Here, the use of negative uniaxial crystal where the ordinary index of refraction n_o is larger than the extraordinary index of refraction n_e is assumed. To obtain an oblique wavefront, either a diffraction grating or a composite prism [7] can be used. If we let both the binary inputs and their logic complements be available, a four output binary two-to-four decoder can be constructed (see fig. 1(b) for logic definition). Here, for simplicity, a rectangular AND gate array is shown. When the two groups of inputs, each containing N channels, are used, the generation of up to N^2 outputs is possible. This network is similar to an optical cross-bar switch [8], except that the roles of the input and output are interchanged. The major attraction of this scheme is that an array of optical AND elements can be monolithically implemented on a single crystal plate. It is, therefore, suitable for optical circuit integration. Using either different input frequencies or different phase-matching directions, either frequency or angle-multiplexed multichannel processings can be performed.

3. SHG-based ultrafast digital multiplication preprocessing.

In general, the SHG gate array is suitable for various applications where a large fast AND gate array is needed. In this letter, an application of a SHG AND element-based array to digital optical multiplication is described. For digital optical multiplication, the conventional digital multiplication via analog convolution (DMAC) [9,10] method uses two processors: an A-O convolver that performs a time-domain binary convolution and an E-O analog-to-digital (A/D) converter [11] that converts the convolution result from a mixed-binary-representation (MBR) to a binary output. Since the binary A-O input is a train of electric signals, this method needs an additional electric-acoustic-optical signal convolution. Furthermore, since the A-O requires a serial input format and its convolution speed depends on the acoustic wave velocity and material response time, its multiplication speed is limited (order of nanosecond). Since the convolution speed increase can reduce the overall multiplication time, next, an all-optical, SHG-based, parallel convolution network is proposed.

Consider (see fig. 2(a)), a 4-bit SHG-based unsigned binary optical convolver with bit spacing $D_x=D_y=D$. Let the two decimal numbers to be multiplied be $A=11$ and $B=14$. Their equivalent binary numbers are $A=1011$ and $B=1110$. The two spatially coded four channel binary numbers A and B arrive from the left and bottom part of the network. In the diagram, the hollow arrow indicates the order of the number sequence progressing from the least significant (LSB) to the most significant bit (MSB). Since at each intersection an AND operation is performed, and since all the sixteen AND outputs (denoted by broken lines) are automatically aligned into seven output spatial channels, these SH output pulses yield the multiplication result $C=1122210$. This MBR output corresponds to the decimal number $C=154$. It can be shown, when the order of both the input and output sequences are reversed, the output $C=91$ represents the product of the two decimal numbers $A'=13$ and $B'=7$.

To generate a signed binary multiplication, an optical two's complement binary (TCB) multiplication is performed [12]. In the TCB representation, a positive binary number stays in an unsigned format but with zero sign bit added in front of its MSB, while a negative binary number is first complemented from its positive counterpart and to it a binary one is added. For example, to multiply the two signed decimal numbers $A=11$ and $B=-14$, we convert them to the TCB representation as $A=01011$ and $B=10010$. Here, the first bit denotes a sign. Since the multiplication of two 5-bit TCB numbers requires nine input and nine output channels [12], four zeros (ones) are inserted between the sign and the MSB. To implement this method, an amended device is used (see fig. 2(b)) where only the lower triangular part of the previous lattice network is used. The upper-half crystal triangle can be replaced by a linear index-matching liquid. With its two parallel inputs, this network can generate the parallel MBR output $C=332220110$. To convert this number back to its TCB format, the number is divided, through the LSB by modulo two, adding the quotient to the next bit, ..., etc. [12]. The converted TCB result equivalent to the decimal number -154 is $C=101100110$.

For the multiplication of two N-bit inputs with bit spacing D and size d, a crystal thickness L, where

$$L=\frac{D(N-1)+d}{\tan(\phi/2)}, \tag{2}$$

is required. A material with a large ϕ reduces the required crystal thickness. Since the time interval, in the same channel, between two consecutive SH output pulses is the travel time difference between the input and the SH signals for the two autochannelized AND gates, the multiplication cycle time T for two N-bit numbers is

$$T=\frac{(N-1)Dn_0(\lambda)\sin(\phi/2)}{c}, \tag{3}$$

where c is the velocity of light in vacuum. With a KDP crystal and input wavelength $\lambda=1064$ nm, $\phi=20.3°$, $n_0(\lambda)=1.494$, and choosing $D_i=1$ mm, the multiplication time for two unsigned 16 bit numbers is about 14 ps. The actual multiplication cycle time depends on the used input pulse duration. Since the temporal width of a SH pulse is always shorter than the fundamental, the use of ultrashort laser pulses can lead to parallel, ultrafast processing.

Since the SHG uses an electronic nonlinearity and assuming a pure crystal, there will be no appreciable induced thermal effect. Because this type of optical network leads to an input power depletion, to obtain N distinguishable output levels, a condition

$$[(2k-1)/2N][1-(1-a)^N]>[1-(1-a)^{k-1}], \quad k=1,2,...,N, \tag{4}$$

where a is the SHG conversion efficiency, needs to be satisfied. For example, for an 8-bit error-free multiplication, a maximum 6% SHG conversion efficiency is allowed. To prevent channel cross-talk, the SH output angular divergence must be restricted. For an input pulse with a bandwidth $\Delta\nu$, the SH output divergence angle β is [5] $\beta=p\Delta\nu/c$ where $p=(4.8\pm0.5)\times10^{-5}$ rad/cm^{-1} and c is the velocity of light in vacuum. For a 10 ps pulse, this angle is a few mrad. As a single-stage parallel algebraic processes, the SHG approach is more compact and much faster than any of the existing E-O and A-O DMAC schemes.

For multi-stage operations, since it is necessary to convert the SH signal back to its fundamental frequency, a parametric frequency down-conversion and amplification scheme can be employed. It is well-known [13], that to convert and amplify a weak SH signal back to its fundamental frequency and power using a parametric scheme, a strong third-harmonic (TH) pump beam is needed. The TH power density is [14]

$$\frac{P}{A}=\frac{1}{8}\frac{n_1n_2n_3}{d_{ij}^2}\frac{(\epsilon_0c)^3g^2}{\omega_1\omega_2}, \tag{5}$$

where the subscripts 1, 3 and 2 denote the weak SH, the strong TH input and the amplified idler output

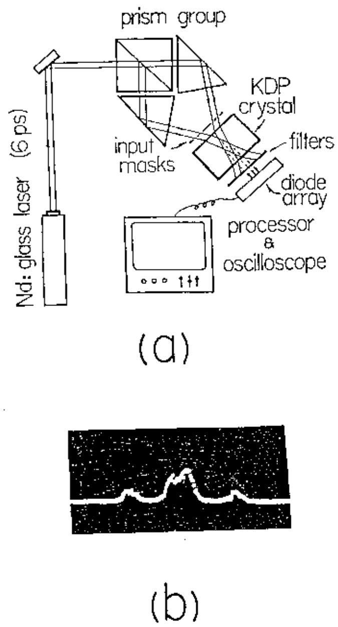

Fig. 3. (a) A SHG-based digital optical multiplication experimental setup. M, mirror; BS, beamsplitter; P, composite prism; KDP, SHG crystal; I, input mask; N, ND filter; C, color filter; D, linear diode array; O, oscilloscope. (b) The oscilloscope trace of a three bit output corresponding to a two-bit binary unsigned multiplication.

signals, while g and d_{ij} are the crystal gain and the second order nonlinearity, respectively. To convert and amplify SH signals from 6% back to 100% power using a 1 cm thick $LiNbO_3$ ($d=5\times10^{-21}$ MKS) cell, about 50 MW/cm^2 pump power density is needed. To decrease this power density, a higher figure of merit M ($M=d^2/n^3$) crystal, such as an organic NPP [15] or a KNbO [16] crystal (where M is an order of magnitude larger than $LiNbO_3$) can be used.

4. Experiment

To demonstrate the operational principle, in fig. 3(a), an experimental setup for the digital optical multiplication of two 2-bit binary numbers is shown. The inputs were 6-ps mode-locked Nd-glass laser pulses. A 1024 channel EG&G linear photodiode array was used to record the SH output. As the SHG material, a 1 cm thick KDP crystal with a 1×2.5 cm^2 rectangular aperture was utilized. For the binary encoding, two masks, each with two slits, were used. To ensure the correct overlap (see eq. (2)), the slit width and spacing were chosen as 0.5 mm and 1.2 mm, respectively. To minimize diffraction effects [5], both the input masks and the signal detection diode array were placed very close to the crystal surfaces. The array was covered both with a 1064 nm absorbing and neutral density filter. The detected signals were scaled and displayed on an oscilloscope. With all the four input slits open, a 3-bit output with intensity levels (1, 2, 1) was observed. In fig. 3(b), an oscilloscope trace showing the experimental result is illustrated. Due to some misalignment and convolution envelope function errors, the width of the center peak is somewhat larger than the two side peaks. Since for KDP ϕ is only 20.3°, with the current crystal, smaller bit size ($d=100$ μm) and spacing ($D=200$ μm) scheme can be used to process a longer bit string ($N=8$). Also, crystals with larger ϕ, such as $LiIO_3$ ($\phi=39.4°$ at $\lambda=1064$ nm), can be used. For real-time operation, input masks scheme can also be replaced by an ultrafast input modulation scheme, such as a parallel all-optical etalon array [17].

5. Summary

To summarize, the use of ultrafast optical SHG effect for an all-optical logic AND operation has been proposed. The major advantages of SHG-based AND operation are: (1) it uses an instantaneous nonlinear optics effect so that ultrafast processing speed can be achieved, (2) it adapts a symmetric input–output format for array interconnection, so that no additional delay elements are needed, (3) both input and output are optical quantities, (4) a SHG AND element based lattice array can be integrated monolithically on a single SHG crystal, and (5) due to the SHG phase-matching property, several processing networks can share a single physical device. A number of SHG-based optical computing architectures and some first-order experimental result were presented.

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