Optical logic gates by nonlinear mixing in BBO

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ABSTRACT

An experimental demonstration of a set of optical logic gates (OR, XOR, AND) is shown using non-linear mixing in a BBO crystal. Pulses generated by a femtosecond Ti:Sapphire laser at 800 nm (140 fs duration, 2nJ/pulse) are split in 4 beams evenly separated in space and propagating collinearly. The 4 beams are focused by a singlet lens in the non-linear crystal and frequency doubled using a type I non-collinear phase matching ($e = o + o$). Due to spherical aberrations of the lens, the 2 beams that are far from the optical axis are brought into a focus that is slightly further away from the focus formed by the 2 beams closer to the optical axis. The frequency-doubled light generated by the two foci propagates in the same direction. An OR gate is produced by constructive interference of the frequency doubled pulses. A XOR gate is produced using destructive interference. OR and XOR can be programmed from a single gate by adjusting time delays of the inputs.
We raise the possibility of creating a cascaded set of gates for a femtosecond time scale computing system using photoinduced absorption in polyacetylene substitutes.

Keywords: optical gates, second harmonic generation (SHG), femtosecond pulses

1. INTRODUCTION

All optical logic gates are the focus of intense research efforts. For optical communication, bitwise logic can be used for address recognition in time division multiplexing system. Demultiplexing data streams can be performed optically at a much faster rate than what is currently achieved electronically [1]. Optical gates using four wave mixing in semiconductors has been proposed and a spectacular AND gate working at 100 Gbit/s has been demonstrated [2]. In this paper, we propose and demonstrate a set of optical logic gate (AND, OR, XOR) with 140 fs resolution based on SHG (second harmonic generation). Non-resonant effects such as Kerr effect, wave mixing (e.g second harmonic generation), occur at subfemtosecond timescales and are therefore candidates for realization of ultra-fast computing machines. We use femtosecond laser pulses from a modelocked Ti:sapphire laser and non linear mixing in a BBO crystal to demonstrate the gate. The output of the gate has twice the optical frequency of the input which makes it hard to cascade gates. We propose a solution to this problem and discuss the requirements for femtosecond computing machines. A 2 bit full adder is described as an example using the proposed optical gates.

2. LOGIC DEVICE

In this section, we describe the working principle of the logic gate. Input data are encoded as streams $X_1(t) \ldots X_{2N}(t)$ of femtosecond pulses (encoded from a single pulse with a pulse shaper) incident at different heights on a diffractive optical element (DOE), which has position dependant focal length as shown in fig 1. All inputs are assumed to be produced by the same laser so that they remain coherent with each other. Data streams are incident symmetrically with respect to the optical axis of the DOE. Inputs at the edge of the DOE (e.g. X_1, X_2) are brought to a focus Y_1 that is further than the focus Y_2 formed by inputs close to the optical axis (e.g. X_{2N}, X_{2N-1}). Each pair of inputs needs to satisfy the non collinear second harmonic phase matching. For moderate group velocity mismatch (short interaction length), the system impulse response function is very narrow and the second harmonic field can be considered to be proportional to the product of the two input fields [3]:

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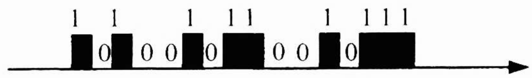
$$Y_i(t) = \kappa X_j(t) X_j(t) \qquad i:1...N, j:1...2N,$$

where κ accounts for the conversion efficiency of SHG.

The logic state value "1" is defined as the presence of a pulse in the stream and "0" when there is no pulse.



Whenever a pulse from the stream $X_1(t)$ collides simultaneously with a pulse of stream $X_2(t)$ in the non-linear crystal, a photon is created at twice the optical frequency which propagates in the direction of the optical axis (fig. 1). By itself, SHG is an AND gate, since a "1" is produced only when two pulses ("1" and "1") are present simultenously ($Y_1 = X_1 X_2$). Interference occurs between the frequency doubled sources generated at the different locations Y_i, i=1..N. We consider for simplicity that the SHG sources located at Y_i, i=1..N are point sources. Interference between short pulses of bandwidth $\Delta\nu$ (typically <10THz) is similar to interference between two broad light source of short coherence length equal to $c/\Delta\nu$ (typically <30 μm). Therefore, for interference to occur, the path length difference between two beams has to be shorter than the coherence length or equivalently, the two pulses need to overlap in time. Constructive or destructive interference takes place depending of the phase difference between the pulse carrier frequency. The phase difference between the generated point sources can be adjusted by time delaying appropriately the inputs. Fig. 2 shows the boolean representation of the optical gate described in fig. 1. The function $F(Y_1... Y_N)$ can perform a set of boolean functions. The function F can be modified by delaying the inputs. In other words, this optical gate can be reconfigured to perform another function by acting on the time delay of the input. If the phase difference between each point source Y_i is a multiple of 2π, constructive interference occurs. In this case, the function F act as an OR function and the output of the device is a sum of product (OR of AND's of two variables). An optical power limiter is placed at the output to equalize the intensity of the pulses.

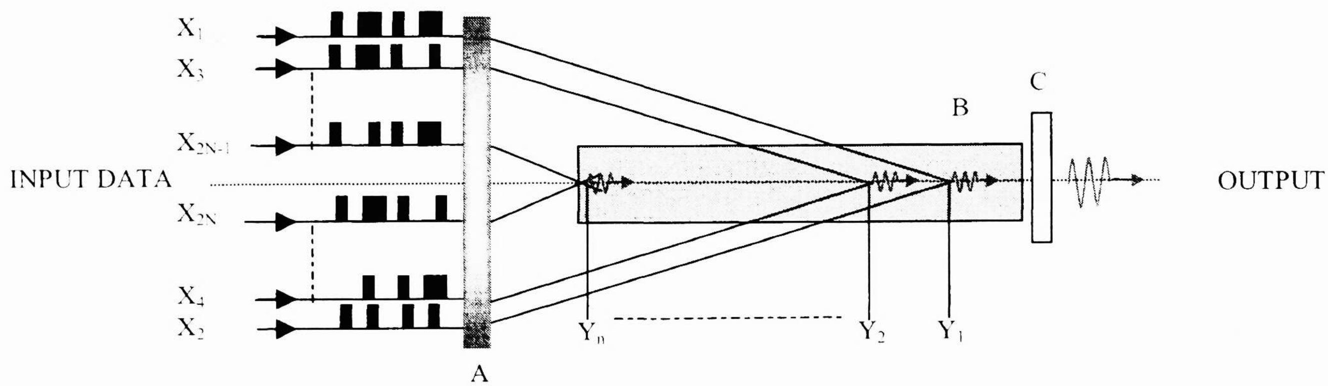


Figure 1: schematic of the optical gate. A: DOE, B: non-linear crystal, C:optical limiter

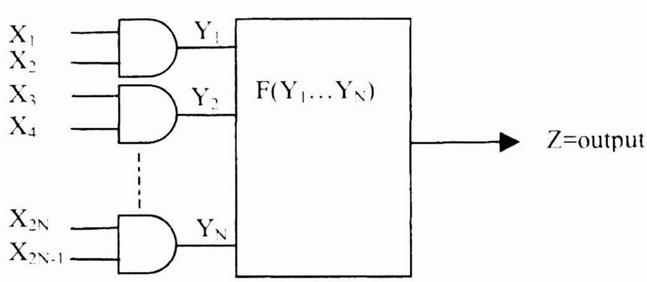


Fig 2: Boolean representation of the optical gate in figure 1.

The principle of operation of this logic device is similar to interfering 2N beams using mirrors and beam splitters (without frequency doubling light). However, the SHG based logic gate does not require beam-splitters, waveplates, mirrors allowing therefore a gain in size reduction of the gate, robustness to vibration because interference is produced within the short distance of the crystal length. The inputs are not destroyed during the process of computation. Other gates can recycle them.

3. EXPERIMENTAL LOGIC GATES

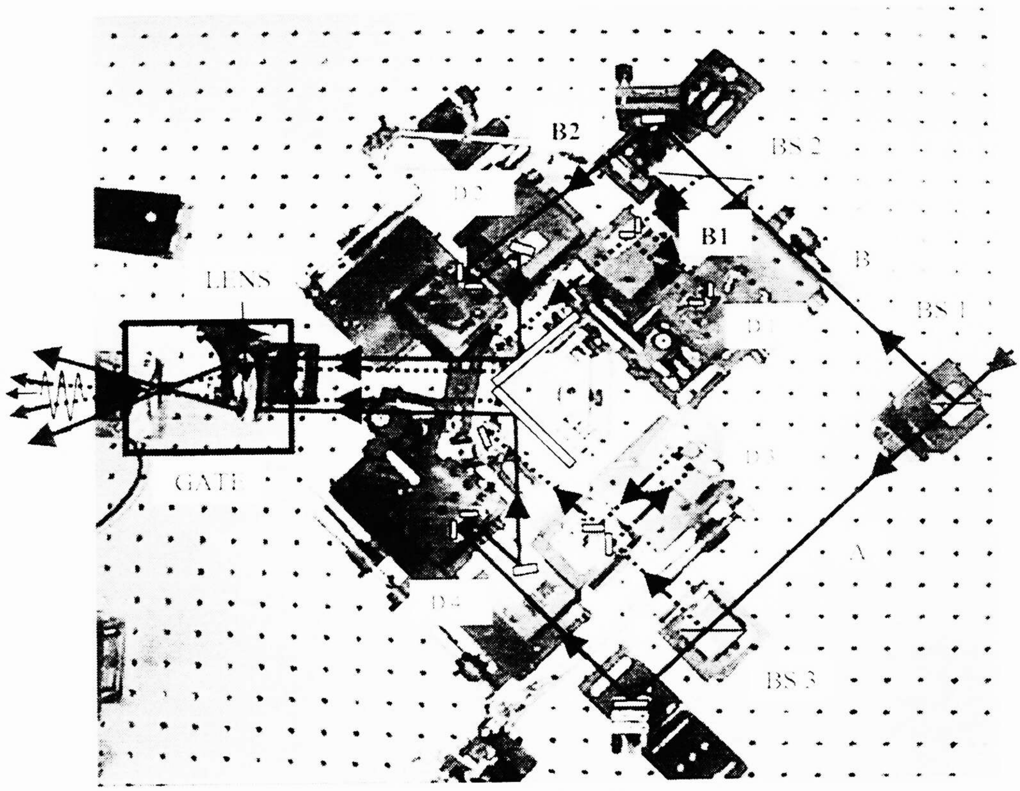


Figure 3: experimental logic gates set-up

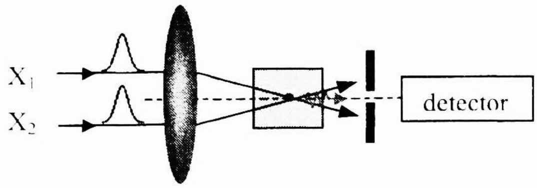
In this section, we present the experimental set-up shown below in fig. 3. Based on the logic device presented in section 1, an AND, OR and XOR gate have been implemented experimentally. 4 beams form the input of the gate and they are generated as follows:

The source is a 76 MHz repetition rate modelocked train of pulses from a Ti:sapphire laser (Coherent MIRA) centered at 800 nm with 140 fs duration and average power 300 mW. The raw beam of 1.5 mm diameter is used throughout the experiment. The incoming beam is split by the non-polarizing beam-splitter BS 1 to produce beam A and B. Beam A is split again by the non-polarizing beam-splitter BS 2, yiedling beam B_1 and B_2. The path length of beam B_1 and B_2 can be adjusted via the delay lines D_1 and D_2 respectively. Beam B1 and B2 are then propagating collinearly towards a lens, separated by 3mm. A similar arrangement for beam A produces two collinear beams separated by 3 mm propagating towards the lens. A total of 4 beams are incident onto a singlet lens of focal length f= 9cm. Each of the 4 beams can be delayed with respect to each other by delay lines controlled by micrometer stages. The purpose of the singlet lens is to implement the DOE discussed in section 1. Here, spherical aberration of the lens is used to obtain a position dependant focal length. The 2 beams incident on the edge of the lens are brought into a focus that is closer than the focus formed by the two beams close to the optical axis (see fig. 4). The lens focuses the four incident beam into a non-linear 0.5 mm thick BBO crystal. Type I phase matching is used ($e= o + o$).

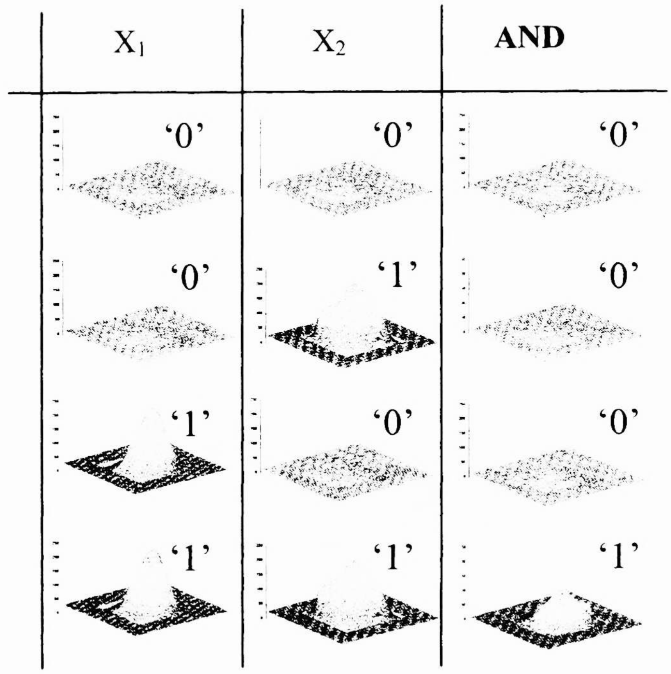
We next show that primitive gates of two inputs AND, OR, XOR can be constructed from the optical device described in fig. 1. We first demonstrate the AND gate:

1. AND GATE

The AND gate is constructed naturally from the property of non-collinear second harmonic generation.



When the two input are simultenously incident on the lens ("1","1"). SHG takes place and generate frequency doubled light. A camera detects the intensity of the pulse at the output. When only one of the beam is present a the input, no frequency doubled light is generated resulting in a logic "0". The relative units on the axis of the second harmonic pulse (right column of the truth table) is not to scale with the units of the IR pulse (columns X_1,X_2). SNR is high for this gate because a logic "0" is given by the detector noise and logic "1" is related to intensity of the second harmonic beam. In the experiment, 50 μW of "blue" light was generated, yielding a SNR of 10^6.



Experimental Truth Table for AND gate

2. OR GATE

An OR gate is more complicated. To build this gate the two inputs X_1 and X_2 are duplicated by splitting each input in two beam. The resulting four beams are incident on the singlet lens as shown below in fig 4 a). The relative delay between X_1 and X_2 is adjusted (see section 3) such as to produce a constructive interference between the two SHG source. The boolean equivalent of this optical gate is shown of fig 4. b).

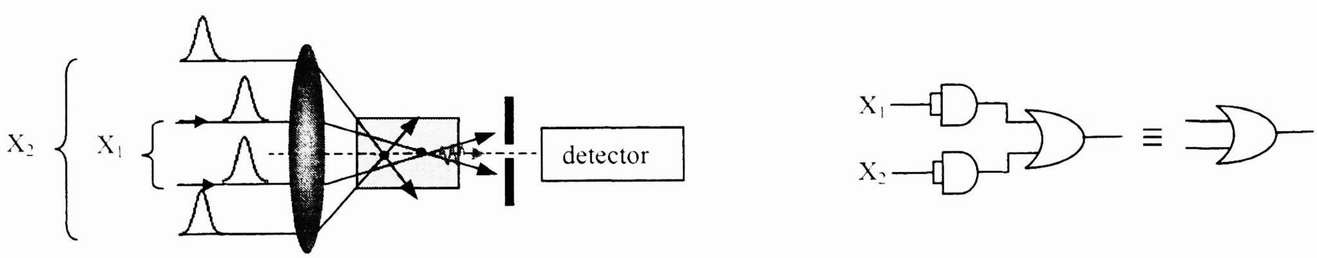
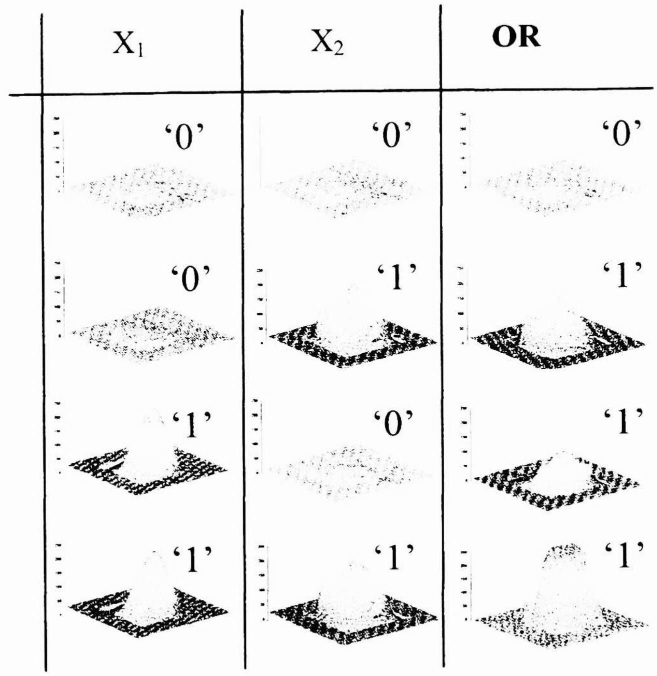


Fig 4 : a) OR optical gate b) boolean representation

Constructive interference increases the detected intensity as can be seen from the result (bottom right pulse in the truth table). The logic "1" represented by the SHG pulse intensity is not constant. Although, this is irrelevant for a single gate, it becomes important for successive cascaded gate. An optical power limiter placed at the output can equalize the intensity of the second harmonic pulses. SNR between a "1" and "0" for this gate is the same as for an AND gate and is equal to 10^6 in this experiment.



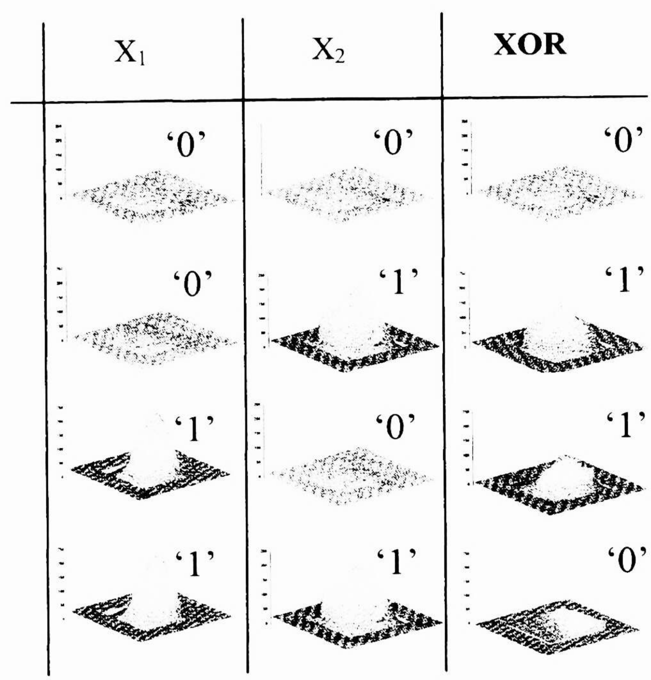
Experimental Truth Table for OR gate

3. XOR gate

The XOR gate works very similarly to the OR gate. The only difference is that the delay is adjusted such as to produce destructive interference.

For this gate, logic state "0" is determined by the destructive interference. Any intensity variation between the two interfering beams causes the level of the "0" to go up, reducing the SNR. SNR is measured to be 7.8. This is due to non-equal intensity of the interfering beam as can be seen from the result of the "1" + "0" and "0" + "1".

Although, the experiment was done with single pulses, it can be generalized to femtosecond pulse trains since the mechanism underlying these gates (second harmonic generation, interference) has subfemtosecond resolution. An inverter gate cannot be realized with these gates because of the nature of the logic state chosen (light or no light). However, interestingly another type of element needed to cascade gates can produce the NOT gate.



Experimental Truth Table for XOR gate

4. CASCADING GATES

This section discusses the problem of gates cascading and presents a possible solution. The wavelength of the output from the gate is half the wavelength of the input signal. For cascading gates, we need to transform the blue wavelength back into IR with fidelity. Frequency down conversion requires 4 wave mixing and looks prohibitively bulky and complicated. Another approach is to use the non-linear property of polymers. Polyacetylene and its substitutes have been studied extensively for their high non-linear susceptibility and ultra fast decay time [4]. For example, poly[(4-tert-butyl-2,6-dimethylphenyl)acetylene] (PMBPA) has a fairly broad absorption spectrum in the visible (350-600 nm) and negligible absorption in the infrared (800 nm). When illuminated with pulses of blue-green light, photoexcitation takes place almost instantaneously (within 10fs), creating electron-hole pairs (fig. 5 a). Ultra short lifetime (130 fs) photoinduced exciton levels are generated close to the conduction band. As a result, photoinduced infrared absorption occurs from the exciton level. In experiments, researchers reported, at room temperature, 10% absorption increase within 10 fs and an absorption time decay equal to 130 fs [4].

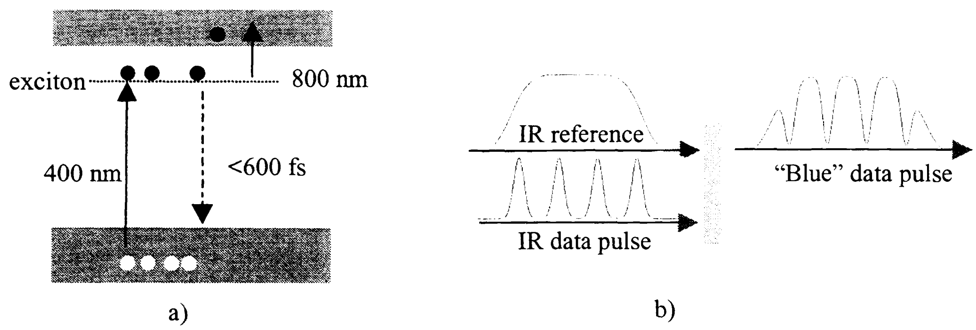


Fig 5: a) photoexcitation of electron-hole pair - simplified band diagram of PMBPA
b) imprinting data on IR beam from visible stream results in an inverted output

To see why this material can be of interest, assume that a long IR pulse is incident on the polymer at the same time as a blue stream of pulses (Fig 5 b). The visible pulses modulate the transmission of IR beam with ultra fast speed (<600fs), causing the IR pulse to be amplitude modulated. The result is an inverted stream of IR pulses with respect to the visible pulse stream (if the extinction is perfect). A NOT gate inverting an IR pulse back in IR requires a 2 stage process: first the IR is frequency doubled with collinear phase matching and then inverted by photoinduced absorption as described above.
An important parameter of the polymer is the magnitude of the photoinduced absorption. High photoinduced absorption is required to produce a NOT gate. Currently, 10% photoinduced absorption has been measured on PMBPA samples. The energy needed to produce the photoinduced absorption was reported to be 10^{16} photons/cm^2. Taking a SHG conversion efficiency of 0.1% and 0.1 μJ/IR pulse , we would need to focus the beam into an area of 1.4 μm^2 to produce 10% of photoinduced absorption. This figure has to be improved both energetically and in the magnitude of the photoinduced absorption.

5. OPTICAL COMPUTATION

In semiconductors, each elementary gates need a power supply in the form of a voltage source. For those optical gates, the reference power supply is a clocked stream of pulses. The reference pulse stream is modulated by the frequency doubled output of previous stages through photoinduced absorption (see section 4) and become the input of the next gate. As an example of computing with this set of optical gates, an implementation of a 2 bits adder is presented.

We denote the two bit numbers to be added (A_0, A_1) and (B_0, B_1). The bits are encoded spatially, therefore we need 4 beams that encode the 2 numbers.

$$\begin{array}{lccc} \text{Carry:} & C_2 & C_1 & \\ & & A_1 & A_0 \\ & & B_1 & B_0 \\ \hline \text{Sum:} & S_2 & S_1 & S_0 \end{array}$$

The LSB S_0 is just an XOR between A_0 and B_0. We use a single optical gate to compute the XOR of two inputs (see section 3) and the first carry C_1 is an AND between the inputs. This block is sketched in fig 6 A.

The second carry C_2 (and the following carries if the number contains more than 2 bits) can be implemented with one gate as an OR of AND's: $C_2 = A_1 C_1 + A_1 B_1 + B_1 C_1$
This block is shown in fig 6. B.

A block computing an XOR of 3 variables is needed to compute S_1. Two XOR and inverting gates are needed:

$$XOR(A_1,B_1,C_1)=XOR(A_1,B_1)\,\overline{C_1} + C_1\,\overline{XOR(A_1,B_1)}$$

The full adder is implemented in fig. 7. using the building blocks of fig 6. Not shown is the "power supply" which consists of a reference stream of pulses.

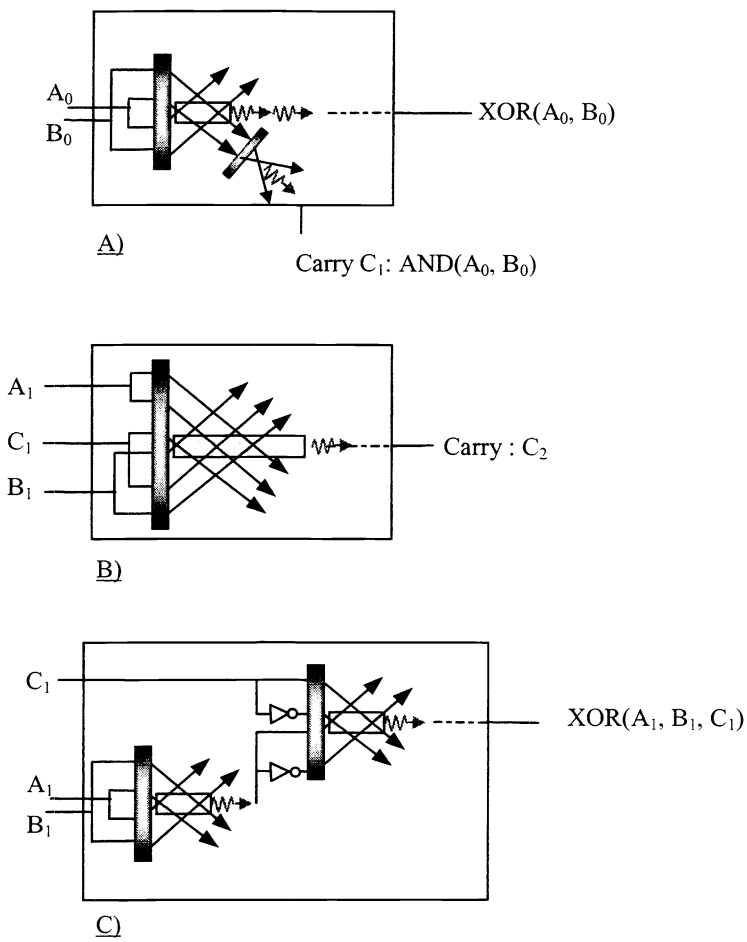


Fig 6: Optical blocks needed to form a full adder
A) *LSB and 1st carry block*
B) *2nd Carry block*
C) XOR of 3 variables

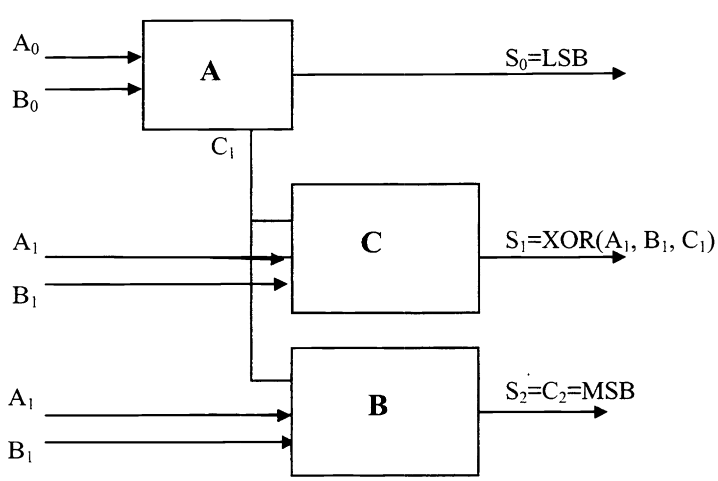


Fig 6: optical layout of a full 2 bits adder

6. CONCLUSION

We have presented and experimentally demonstrated the set of elementary gates AND, OR, XOR using second harmonic generation in BBO. We argue that cascadable gates can be implemented using photoinduced absorption in polyethylene substitutes. A two bit adder is described using the proposed set of optical gates. Ultra high speed computing (10 THz) can be realized with this all optical logic elements.

7. REFERENCES

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