Terahertz optical asymmetric demultiplexer based tree-net architecture for all-optical conversion scheme from binary to its other 2^n radix based form

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To exploit the parallelism of optics in data processing, a suitable number system and an efficient encoding/decoding scheme for handling the data are very essential. In the field of optical computing and parallel information processing, several number systems like binary, quaternary, octal, hexadecimal, etc. have been used for different arithmetic and algebraic operations. Here, we have proposed an all-optical conversion scheme from its binary to its other 2^n radix based form with the help of terahertz optical asymmetric demultiplexer (TOAD) based tree-net architecture.

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The new generation of communication networks is moving towards terabit per second data rates. Such data rates can be achieved if the traditional carrier of information, electrons, are replaced by photons for devices based on switching and logic. Researches into this field have also explored new concepts and ideas. Various architectures, algorithms, logical and arithmetic operations have been proposed in the field of optical/optoelectronic computing and parallel processing in last few decades[1−8]. To exploit the parallelism of optics in computing, a suitable number system and an efficient encoding/decoding scheme for handling the data are very essential. In the field of optical computing and parallel information processing, several number systems like binary, quaternary, octal, hexadecimal, etc. have been used for different arithmetic and algebraic operations. These numbers are 2^n radix based numbers where n is an integer. For a number represented in binary form the value of n is 1, for quaternary $n = 2$, for octal $n = 3$ and for hexadecimal $n = 4$. Therefore an efficient conversion scheme from one number system to another is very essential. Binary number is accepted as the best representing number system in almost all types of existing computers. The main advantages of the use of 2^n radix based number are their easier type of representation and easier conversion from one 2^n radix based number to other 2^n radix based number. In this paper, we have proposed an all-optical parallel conversion scheme of binary number to its other 2^n radix based form with the help of terahartz optical asymmetric demultiplexer (TOAD) based tree-net architecture. High speed (Tb/s) operation can be achieved by this all-optical scheme.

Sokoloff *et al.* demonstrated a new device TOAD capable of demultiplexing data at 50 Gb/s[9]. TOAD based processing has been of great interest in the last few years[10−13]. In almost all the above cases, the transmitting mode of the device (output port) is used to take the output signal. But the signal that exits from the input port (reflecting mode) remains unused. In this paper, we have tried to take the output signal from both the transmitting and reflecting mode of the device. That is, light coming out from both the input port and output port is taken into account. In our earlier contribution, we proposed a TOAD-based tree architecture, a new and alternative scheme, for all-optical logic and arithmetic operations[14,15]. In this paper, the same TOAD-based tree-net architecture has been tactfully used to design an all-optical conversion scheme from binary number to its other 2^n radix based form which is from binary to octal, binary to hexadecimal etc. The possibility of practical implementation of the proposed scheme is also discussed. The proposed all-optical scheme can exhibit their switching speed far above present electronic switches.

The TOAD consists of a loop mirror with an additional, intraloop 2×2 (ideally 50:50) coupler. The loop contains a control pulse (CP) and a nonlinear element (NLE) that is offset from the loop's midpoint by a distance Δx as shown in Fig. 1[9]. A signal with field $E_{\rm in}(t)$ at angular frequency ω is split in coupler and travels in clockwise (cw) and counter clockwise (ccw) direction through the loop. The electrical field at port-1 and port-2 can be expressed as follows[10]:

$$E_{\rm out,1}(t) = E_{\rm in}(t - t_{\rm d}) \cdot {\rm e}^{-j\omega t_{\rm d}} \times \left[d^2 \cdot g_{\rm cw}(t - t_{\rm d}) - k^2 \cdot g_{\rm ccw}(t - t_{\rm d})\right], \quad (1)$$

$$E_{\rm out,2}(t) = jdkE_{\rm in}(t - t_{\rm d}) \cdot {\rm e}^{-j\omega t_{\rm d}} \times \left[g_{\rm cw}(t - t_{\rm d}) + g_{\rm ccw}(t - t_{\rm d})\right], \quad (2)$$

where $t_{\rm d}$ is the pulse round trip time within the loop as shown in Fig. 1. Coupling ratios k and d are for the cross

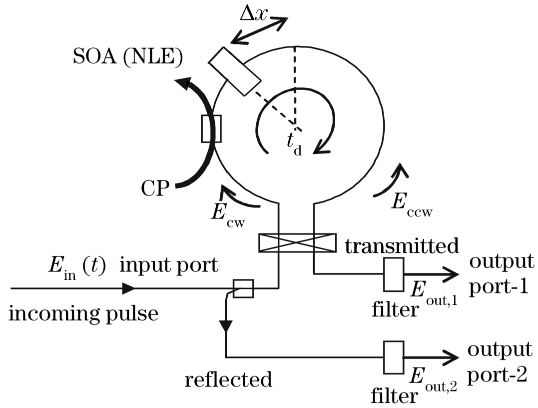

Fig. 1. TOAD-based optical switch.

and through coupling respectively. The cw and ccw traveling signal will be amplified by the complex field gain $g_{\mathrm{cw}}(t)$ and $g_{\mathrm{ccw}}(t)$, respectively. The output power at port-1[13] can be expressed as

$$\begin{aligned} P_{\mathrm{out},1}(t) &= \frac{P_{\mathrm{in}}(t-t_{\mathrm{d}})}{4}\cdot[G_{\mathrm{cw}}(t)+G_{\mathrm{ccw}}(t) \\ &\quad -2\sqrt{G_{\mathrm{cw}}(t)\cdot G_{\mathrm{ccw}}(t)}\cdot\cos(\Delta\varphi)] \\ &= \frac{P_{\mathrm{in}}(t-t_{\mathrm{d}})}{4}\cdot SW(t), \end{aligned} \quad (3)$$

where $SW(t)$ is the transfer function, and the phase difference between cw and ccw pulse $\Delta\varphi=(\varphi_{\mathrm{cw}}-\varphi_{\mathrm{ccw}})$. $G_{\mathrm{cw}}(t)$, $G_{\mathrm{ccw}}(t)$ are the power gain. The power gain is related to the field gain as $G = g^2$ and $\Delta\varphi = -\frac{\alpha}{2}\cdot\ln\left(\frac{G_{\mathrm{cw}}}{G_{\mathrm{ccw}}}\right)$, where α is the line-width enhancement factor.

Now we will calculate the power at port-2:

$$\begin{aligned} P_{\mathrm{out},2}(t) &= \frac{1}{2}E_{\mathrm{out},2}(t)\cdot E^*_{\mathrm{out},2}(t) \\ &= d^2k^2\cdot P_{\mathrm{in}}(t-t_{\mathrm{d}})\cdot g^2_{\mathrm{cw}}(t-t_{\mathrm{d}})\cdot\left\{1+\frac{g^2_{\mathrm{ccw}}(t-t_{\mathrm{d}})}{g^2_{\mathrm{cw}}(t-t_{\mathrm{d}})}\right. \\ &\quad \left.+2\cdot\frac{g_{\mathrm{ccw}}(t-t_{\mathrm{d}})}{g_{\mathrm{cw}}(t-t_{\mathrm{d}})}\cdot\cos\left[\varphi_{\mathrm{cw}}(t-t_{\mathrm{d}})-\varphi_{\mathrm{ccw}}(t-t_{\mathrm{d}})\right]\right\} \\ &= d^2k^2\cdot P_{\mathrm{in}}(t-t_{\mathrm{d}})\cdot G_{\mathrm{cw}} \\ &\quad \times\left[1+\frac{G_{\mathrm{ccw}}}{G_{\mathrm{cw}}}+2\cdot\sqrt{\frac{G_{\mathrm{ccw}}}{G_{\mathrm{cw}}}}\cdot\cos(\Delta\varphi)\right] \\ &= d^2k^2\cdot P_{\mathrm{in}}(t-t_{\mathrm{d}}) \\ &\quad \times\left[G_{\mathrm{cw}}+G_{\mathrm{ccw}}+2\cdot\sqrt{G_{\mathrm{ccw}}\cdot G_{\mathrm{cw}}}\cdot\cos(\Delta\varphi)\right]. \end{aligned} \quad (4)$$

For an ideal 50:50 coupler, $d^2 = k^2 = 1/2$. In the absence of control signal, the data signal (incoming signal) enters the fiber loop and passes through the semiconductor optical amplifier (SOA) at different times when counter-propagating around the loop, experiencing the same unsaturated amplifier gain G_0, and recombining at the input coupler[11], i.e., $G_{\mathrm{ccw}} = G_{\mathrm{cw}}$. Then $\Delta\varphi = 0$ and expression for $P_{\mathrm{out},1}(t) = 0$ and $P_{\mathrm{out},2}(t) = G_0\cdot P_{\mathrm{in}}$. It shows that the data are reflected back toward the source. When a control pulse is injected into the loop, it saturates the SOA and changes its index of refraction. As a result, the two counter-propagation data signal will experience different gain saturation profiles, i.e., $G_{\mathrm{ccw}} \neq G_{\mathrm{cw}}$. Therefore, when they recombine at the input coupler, the data will exit from the output port-1. In this case, Eq. (3) can be expressed as $P_{\mathrm{out},1}(t) = \frac{P_{\mathrm{in}}(t-t_{\mathrm{d}})}{4}\cdot SW(t)$ and $P_{\mathrm{out},2}(t) \simeq 0$. The result of numerical simulation with Matlab7.0 has been shown in Fig. 2. In this simulation, α was taken 9.5 and the ratio $G_{\mathrm{ccw}}/G_{\mathrm{cw}}$ was taken 0.52.

A polarization or wavelength filter may be used at the output to reject the control and pass the input pulse. As shown in Fig. 1, it is clear that in the absence of control signal, the incoming pulse exits through input port of TOAD and reaches to the output port-2. In this case, no light is present in the output port-1. But in the presence of control signal, the incoming signal exits through output port of TOAD and reaches to the output port-1. In this case, no light is present in the output port-2. In the absence of incoming signal, port-1 and port-2 receive no light as the filter blocks the control signal. Schematic block diagram is shown in Fig. 3 and the truth table of the operation is given in Table 1.

TOAD-based switching system which is discussed above can successfully be used to design optical tree-like architecture (OTA). In a tree structure, the single light beam breaks into several distributed branches and subbranch paths as shown in Fig. 4. For this purpose, three TOAD-based optical switches s_1, s_2 and s_3 are to be set at N, O and P, respectively. Now, let us consider there is

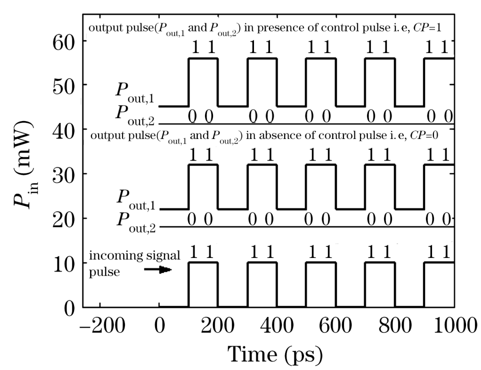

Fig. 2. Simulation result.

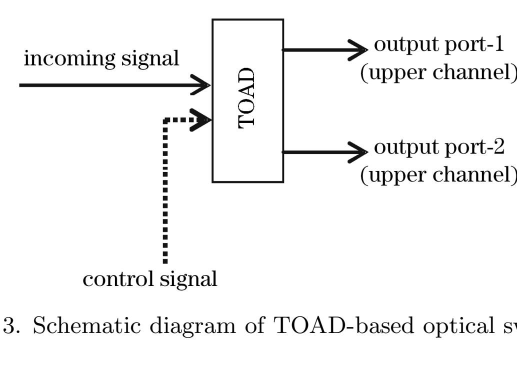

Fig. 3. Schematic diagram of TOAD-based optical switch.

Table 1. Truth Table of Fig. 1

Incoming Signal	Control Signal	Output Port-1	Output Port-2
0	0	0	0
0	1	0	0
1	0	0	1
1	1	1	0

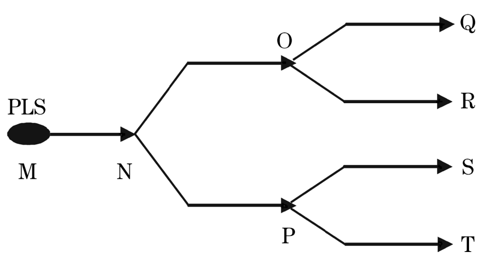

Fig. 4. Optical tree architecture.

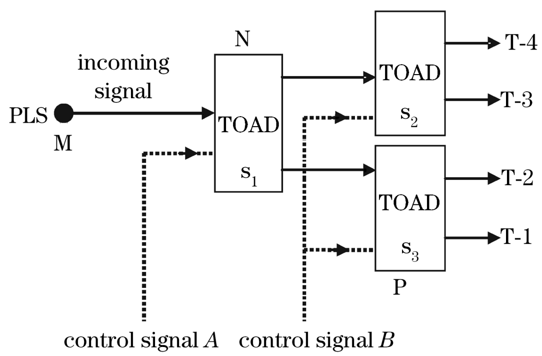

Fig. 5. TOAD-based optical switch in a tree architecture.

a pulse light source (PLS) which may be a laser source. The light signal that comes from PLS can be taken as the incoming signal. The incoming light signal incidents on the switch s_1 first. Now we can get the light in different desired branches or sub-branches by properly placing the control signals. Control signals are also the light signals. The schematic diagram is shown in Fig. 5. Here we make a cascade between several TOADs. The techniques of cascading of two TOADs were experimentally shown by Wang *et al.*[12]. In such configuration, one TOAD has the SOA on the same side of loop as the control port and the other has the SOA on the opposite side of the loop as control port. Their switching windows are then placed such that the sharp edge of one overlaps the sharp edge of the other TOAD that results the switching window size limited only by the optical pulsed width of the clock and data. Here, the overall transfer function is given by[12]

$$\text{Cascade}\,(t,\delta) = SW_1(t) \times SW_2(t-\delta), \tag{5}$$

where δ is the delay offset time. The input power of TOAD s_2 and s_3 are $[P_{\text{out},1}(t)]_{s_1}$ and $[P_{\text{out},2}(t)]_{s_1}$, respectively. Here, we have two control signals A and B which can take two binary values 1 and 0. The presence of light beam is considered to be as one (1) state and the absence of light beam is zero (0) state. Hence, we can control A and B in four ways: $A=0$, $B=0$; $A=0$, $B=1$; $A=1$, $B=0$; $A=1$, $B=1$.

Let us explain the working principle of optical tree-like structure using TOAD-based optical switches as shown in Fig. 5 in detail.

Case 1: When $A=0$ and $B=0$

The light that comes from PLS is incident on switch s_1 first. As $A=0$, the control signal A is absent. That means only the incoming light signal is present at s_1. As per the switching principle, discussed above, the light emerges through lower channel and falls on switch s_3 at P. Here the control signal B is also absent. That also means only the incoming light signal is present at s_3. Hence, the light finally comes out through lower channel of s_3 and reaches at T-1 (terminal-1). In this case, no light is present at other terminals T-2 (terminal-2), T-3 (terminal-3) and T-4 (terminal-4). So T-1 is in one state and others are in zero state when $A=B=0$.

Case 2: When $A=0$ and $B=1$

As $A=0$, light beam emerges through lower channel and falls on s_3. At s_3, the control signal B is present. In the presence of control signal, the incoming light signal emerges through upper channel of s_3 and finally reaches at T-2. In this case, the light is only present in T-2. Hence, T-2 is in one state and others are in zero state, when $A=0$ and $B=1$.

Case 3: When $A=1$ and $B=0$

As $A=1$, the control signal A is present. Therefore, the light emerges through upper channel of s_1 and falls on s_2 at O. As $B=0$, no control signal is present at B. That means the light comes out from lower channel of s_2 to reach at T-3. So the T-3 is in one state and others are in zero state when $A=1$ and $B=0$.

Case 4: When $A=1$ and $B=1$

As $A=1$, the input control signal A is present. Therefore, the light emerges through upper channel of s_1 and falls on s_2 at O. As $B=1$, the control signal is present at B. Hence, the light follows the upper channel of s_2 to reach at T-4. So the T-4 is in one state and others are in zero state when $A=1$ and $B=1$.

Above observations are put on Table 2. This gives the output state of different output terminals for different values of A and B in tree architecture. Now we consider the control signals as the binary inputs and the presence of light beam as one (1) state and absence of light beam as zero (0) state.

Now, if the control signals are taken as binary input and the output terminals are marked by numbers (quaternary/octal/hexadecimal etc.), such as T-1 corresponds to 0, T-2 corresponds to 1, T-3 corresponds to 2, then above tree architecture (forward) can be used as binary to quaternary/octal/hexadecimal conversion scheme.

Since each of the n inputs can be 0 or 1, there are 2^n possible input combinations or codes. For each of the

Table 2. State of Different Output Terminals for Different Values of A and B in Tree Architecture

Input		Output at Different Terminals			
A	B	T-1	T-2	T-3	T-4
0	0	1	0	0	0
0	1	0	1	0	0
1	0	0	0	1	0
1	1	0	0	0	1

input combinations, only one of the 2^n outputs will be active (presence of light), and all other outputs will remain inactive (absence of light). Now, the above tree architecture can act as an all-optical n-line to 2^n converter. For $n = 2$ it will act as binary to quaternary converter, for $n = 3$ it will act as binary to octal converter, for $n = 4$ it will act as binary to hexadecimal converter, and so on.

· Binary to quaternary conversion

The above tree architecture, as shown in Fig. 5, can be used as binary to quaternary conversion scheme. Table 1 shows that Fig. 5 can be used as binary to quaternary converter.

· Binary to octal conversion

For a binary to octal converter, we need three control signals based tree architecture as shown in Fig. 6. As the control signals are considered as input signals, there are 2^3 (= 8) different input combinations. Depending on the state of input variables (A, B, C) (these are also the light signals), the output is obtained from output T-1 to output T-8. The eight cases are described in detail.

Case 1: When $A = 0$, $B = 0$, $C = 0$

The light from PLS is incident on switch s_1. As the control signal A is absent, the light emerges through lower channel of s_1 to fall on s_3. Due to the absence of control signal B, the light follows the path of lower channel of s_3 and reaches to switch s_7. Finally the light beam comes at output T-1 through lower channel of s_7 as the control signal C is absent. In this case, output T-1 only receives light while the other seven output terminals do not receive any light. Hence, T-1 is in one state and others are in zero state when $A = B = C = 0$.

Case 2: When $A = 0$, $B = 0$, $C = 1$, the light from PLS reaches output T-2.

Case 3: When $A = 0$, $B = 1$, $C = 0$, the light beam reaches output T-3.

Case 4: When $A = 0$, $B = 1$, $C = 1$, output T-4 receives light.

Case 5: When $A = 1$, $B = 0$, $C = 0$, the light from PLS reaches output T-5.

Case 6: When $A = 1$, $B = 0$, $C = 1$, light signal reaches output T-6.

Case 7: When $A = 1$, $B = 1$, $C = 0$, output T-7 receives the light.

Case 8: When $A = 1$, $B = 1$, $C = 1$, the light reaches at output T-8.

Above findings are put in Table 3 which shows that the scheme in Fig. 6 can be used as binary-to-octal

Table 3. State of Different Output Terminals for Different Input Variables (Three Input) in OTA

Input			Output State at Different Output Terminals							
A	B	C	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8
0	0	0	1	0	0	0	0	0	0	0
0	0	1	0	1	0	0	0	0	0	0
0	1	0	0	0	1	0	0	0	0	0
0	1	1	0	0	0	1	0	0	0	0
1	0	0	0	0	0	0	1	0	0	0
1	0	1	0	0	0	0	0	1	0	0
1	1	0	0	0	0	0	0	0	1	0
1	1	1	0	0	0	0	0	0	0	1

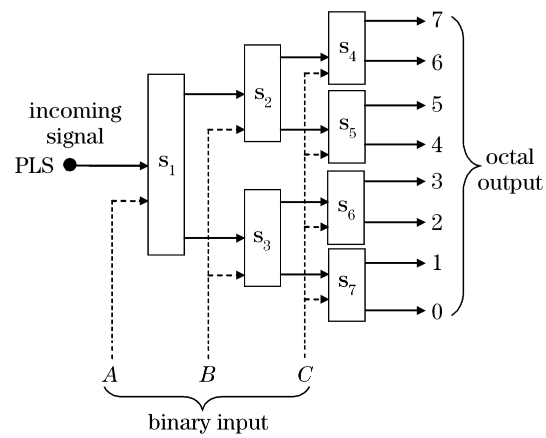

Fig. 6. Circuit for all-optical conversion scheme: binary to octal.

decoder. Here, the presence of light in output terminal is taken as in one state and the absence of light is taken as in zero state.

Now, the above tree architecture, as shown in Fig. 6, can be used as binary to octal conversion scheme.

· Binary to hexadecimal conversion

The use of four control signals as the binary input will transform the device to a binary-to-hexadecimal converter. This can be done by proper incorporation of TOAD-based optical switches, vertical and horizontal extension of the tree and suitable branch selection.

In conclusion, the main advantage of the proposed scheme is that the process is all-optical in nature and bears the inherent advantages of tree architecture. Applying the proper control signals, one can send the input signal to any one of the desired output channels. The scheme can easily and successfully be extended and implemented for higher number scheme. Interestingly, this proposed scheme can also be used for the conversion of binary to ternary/quinary/senary/septenary/nonary /decimal etc. It is important to note that the above discussions are based on a simple model. To experimentally achieve the result from the proposed scheme, some design issues have to be considered, for example, walk-off problem due to dispersion, polarization properties of fiber, predetermined values of the intensities/wavelength of laser light for control and incoming signals, introduction of filter, intensity losses due to fiber couplers, etc. Time delay, nonlinear phase modulation, cross talk, extinction ratio and synchronization of signals are also the important issues. Lasers with wavelengthes of 1552 and 1534 nm can be used as input/control signal, respectively. Intensity losses due to couplers in interconnecting stage may not create much trouble in producing the desired optical bits at the output as the whole system is digital one.

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