

13. S. Palaniandy and N.H. Jamil, Influence of milling conditions on the mechanochemical synthesis of CaTiO_3 nanoparticles, *J Alloys Compd* 476 (2009), 894–902.
14. M. Shivaram R.H. Krishna, H. Nagabhushana, S.C. Sharma, B.M. Nagabhushana, B.S. Ravikumar, R.P.S. Chakradhar, Synthesis, characterization, EPR and thermoluminescence properties of CaTiO_3 nanophosphor. *Mater Res Bull* 48 (2013), 1490–1498.
15. D. Talantikite and L. Taïbi-Benziada, Phase transitions of CaTiO_3 ceramics sintered with the aid of NaF and MgF_2 , *Solid State Sci* 11 (2009), 151–155.
16. Y.J. Wong, J. Hassan, and M. Hashim, Dielectric properties, impedance analysis and modulus behavior of CaTiO_3 ceramic prepared by solid state reaction, *J Alloys Compd* 571 (2013), 138–144.
17. B.W. Hakki and P.D. Coleman, A dielectric resonator method of measuring inductive capacities in the millimeter range *IRE Trans Microwave Theory Tech*, 8 (1960), 402–410.
18. M.A.S. Silva, T.S.M. Fernandes, and A.S.B. Sombra, An alternative method for the measurement of the microwave temperature coefficient of resonant frequency (τ_f), *J Appl Phys* 112 (2012), 074106.
19. L. Bleicher, J.M. Sasaki, and C.O.P. Santos, *J Appl Cryst* 33 (2000), 1189.
20. A.J. Moulson and J.M. Herbert, *Electroceramics: materials-properties-applications*, Wiley, Hoboken, NJ, 2003, 2nd Ed., ISBN 0471–49748-7.
21. K.M. Luk and K.M. Leung, *Dielectric resonator antennas*, 1st ed., Research Studies Press, 2003, ISBN 0-86380-263-X.
22. A. Petosa, *Dielectric resonator antenna handbook*, Artech-House, Norwood, MA, 2007, 307p, ISBN-13:978-1-59693-206-7.

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MULTIFUNCTION OPTOELECTRONIC GATE

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ABSTRACT: A multifunction optoelectronic gate that can perform as any desired logic gate of two variables was theoretically proposed and a simplified version is experimentally demonstrated. The proposed optoelectronic gate is dynamically configurable, and being wavelength independent, it can act on multiple input optical bits and realize different functions simultaneously. © 2015 Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 57:969–972, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29001

Key words: logic gates; optical logic; optical signal processing; data mining

1. INTRODUCTION

All-optical and optoelectronic logic gates are very promising for high bandwidth applications. Especially, exclusive OR (XOR) and exclusive NOR (XNOR) logic gates are very useful in applications such as label switching, parity checking, and pattern recognition [1]. Previous attempts on building all-optical logic gates make use of nonlinear loop mirrors [2], nonlinearities in semiconductor optical amplifiers [1], or chaotic two-section lasers [3]. Another optoelectronic approach is based on an optoelectronic bistable switch consisting of a phototransistor and a LED [4], or photoconducting and electroluminescent thin films

[5]. However, all of these applications are wavelength dependent and cannot process multiple signals at different wavelengths at the same time. An earlier attempt by Hansen and Gnauck, based on a dual drive Mach–Zehnder modulator, realized an XOR/XNOR only gate; however, other logic functions were not possible with this earlier setup [6]. In this article, we propose a wavelength independent optoelectronic multifunction gate design that can be dynamically modified to perform as any classical logic gate of two variables. Our proposed approach can act on many input signals simultaneously making use of the large bandwidth the optical domain offers. We have experimentally built a subset of the proposed configuration and used the optical logic gate as an XNOR gate and demonstrated data mining in a real time streaming input data, assuming that we have no prior knowledge about the data bit stream, except the data rate.

2. MULTIFUNCTION OPTOELECTRONIC GATE

The proposed multifunction optoelectronic gate consists of three 1×2 (one input, two output) interferometric switches (IS) and four amplitude modulators as seen in Figure 1. If a voltage equal to V_π is applied to an IS, all of the input light is directed to output Port 1 (shown with bold line in Fig. 1.); similarly when the applied voltage is equal to 0 Volts, then all of the input light is directed to output Port 2 (shown with double line in Fig. 1.). An optical 1 bit is defined as an optical pulse, and the optical 0 bit is defined as no light present. Similarly, an electrical 0 bit is defined as zero voltage while an electrical 1 bit is defined as the voltage value of V_π . The proposed multifunction logic gate takes two electrical bits (x and y) and an optical bit of 1 (i.e., an optical pulse) as inputs, and it outputs an optical bit that is a function of x and y . This function $f(x,y)$ can be dynamically configured to match any possible Boolean function (i.e. logic gate) of two variables.

When an electrical data bit x , where x is either 0 or 1, is applied to the first interferometric switch (IS-1), it can be shown that the output of the Port 1 of IS-1 is given by x and the output of Port 2 is given by the logical negation of x denoted as \bar{x} , assuming the optical input to this first IS is an optical 1 (i.e. an optical pulse), as seen in Figure 1.

The second and third interferometric switches (IS-2 and IS-3) are both driven electrically by the other bit y (again either 0 or 1), and their optical inputs are x and \bar{x} , respectively. Each IS realizes two multiplication operations simultaneously; first it multiplies the optical input bit and the electrical input bit, and second it multiplies the optical input bit and the negation of the electrical input bit. As a result, after the second and third IS we obtain four multiplications as optical signals, those are: $(x \cdot y)$, $(x \cdot \bar{y})$, $(\bar{x} \cdot y)$, and $(\bar{x} \cdot \bar{y})$. The reader should note that, for any

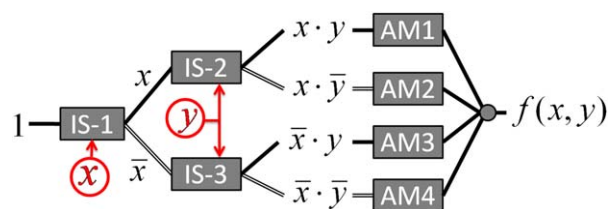


Figure 1 Multifunction Optoelectronic Gate layout. IS: interferometric switch, AM: amplitude modulator, x and y are logical bits, where electrical bits are shown in red circles, optical bits are shown in black. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

TABLE 1 Some Examples of Boolean Functions

(a_1, a_2, a_3, a_4)	Boolean Function $f(x, y)$
(1,0,0,0)	AND Gate
(0,1,1,1)	NAND Gate
(1,1,1,0)	OR Gate
(0,0,0,1)	NOR Gate
(0,1,1,0)	XOR Gate
(1,0,0,1)	XNOR Gate
(1,1,1,1)	TRUE
(0,0,0,0)	FALSE
(0,0,1,1)	NOT x
(0,1,0,1)	NOT y
(1,1,0,0)	x
(1,0,1,0)	y

combination of x and y , only one of these four multiplication signals will be equal to 1, and the other three signals will be 0. This fact prevents an interference from happening between these channels. Each of these four optical signals passes through different optical amplitude modulators (AM1–AM4) which can turn on or off each of these channels individually. These four channels are optically added and the resulting output function $f(x, y)$ is given as:

$$f(x, y) = a_1(x \cdot y) + a_2(x \cdot \bar{y}) + a_3(\bar{x} \cdot y) + a_4(\bar{x} \cdot \bar{y}),$$

where a_1 through a_4 are either 1 or 0, denoting whether the corresponding optical channel is on or off (The reader should note that there are 16 different functions possible). These four multiplication signals, coming from each channel, mathematically constitute a complete product set of Boolean algebra with two variables [7]. As a result, one can realize all 16 different Boolean functions of two variables. In other words, the setup can dynamically change its configuration by turning the amplitude modulators on or off, and act as any desired logic gate. For example, if AM1 and AM4 are open (i.e., $a_1 = a_4 = 1$) and the other channels are off (i.e., $a_2 = a_3 = 0$), the resulting Boolean function is $(x \cdot y) + (\bar{x} \cdot \bar{y})$, which is identical to an XNOR Gate. Some of these Boolean functions and the corresponding logic gates are listed in Table 1.

Another important point to note is that, the proposed multifunction optoelectronic gate setup works independent of the input wavelength. It means that, if one replaces the standard amplitude modulators with wavelength dependent spatial amplitude modulators, the same setup can act as different logic gates for different wavelengths at the same time. For example, the proposed setup can act as an XOR Gate for λ_1 , and as an OR Gate for λ_2 simultaneously. This property makes parallel computation possible with our proposed setup.

3. 8 BIT TARGET PATTERN EXTRACTION

Due to not having all the necessary optoelectronic components, a simplified setup has been built to experimentally demonstrate our method as shown in Figure 2. The experimental setup is chosen as an optoelectronic XNOR-only gate. In this simplified proof-of-concept setup, IS2 and IS3 are replaced with simple amplitude modulators as the output of an amplitude modulator can be made identical to the any output port of an IS under the correct bias voltage. Also, the necessary channels are directly combined without passing through additional amplitude modulators unlike the proposed setup shown in Figure 1.

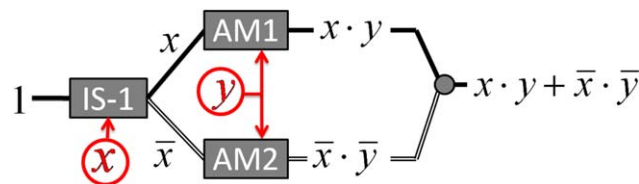


Figure 2 The optoelectronic XNOR logic gate, a simplified version of the multifunction optoelectronic gate. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

This XNOR-only logic gate was used in a data mining application, where an 8 bit long target data is searched in the streaming data. The input data stream, $x(t)$, used in the experiment is the 40 bit long word “CREOL” written in binary code as follows: “01000011-01010010-01000101-01001111-01001100.” The 8 bit long target pattern, $y(t)$, was chosen as the letter “R” in binary, which is “01010010.” The setup compares the streaming data and the target pattern bit by bit through XNOR operation, and outputs an optical 1 if the two bits are the same and an optical 0 if the two bits are different. To detect an n bit long target pattern inside the streaming input data, all bits of the target signal from y_1 to y_n should match to input data bits x_{m+1} to x_{m+n} one by one resulting in n consecutive 1 bits, synchronized with the target signal at the output, confirming both the existence and the location of the target pattern in the input data stream. These n consecutive optical 1 bits can be counted electronically, or sent to an optical integrator to improve the signal to noise ratio [8].

The output of the system that detected the target pattern is shown in Figure 3. As expected, all 8 bits of the target pattern match one by one to the corresponding bits in the input data stream between $2 \mu\text{s}$ and $4 \mu\text{s}$. The on/off ratio of the resulting system was 11 dB. The data rate used in the experiment was 4 Mbit/s and is limited by the electronic data generators used in the experiment. The small glitches that occur at the edges of the bit windows are due to input optical signal being a CW light instead of a pulse train.

It is clear that with this approach the relative timing between the input data signal and the target pattern is vital. If y_1 does

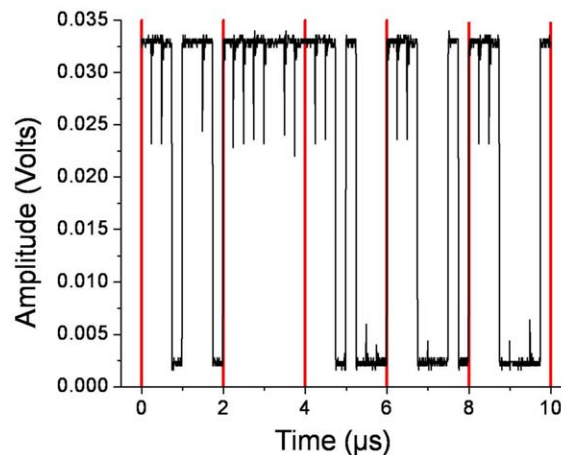


Figure 3 Output of the system for 8 bit target pattern extraction. In the time slot, between $2 \mu\text{s}$ and $4 \mu\text{s}$, there exist eight consecutive “1” bits. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

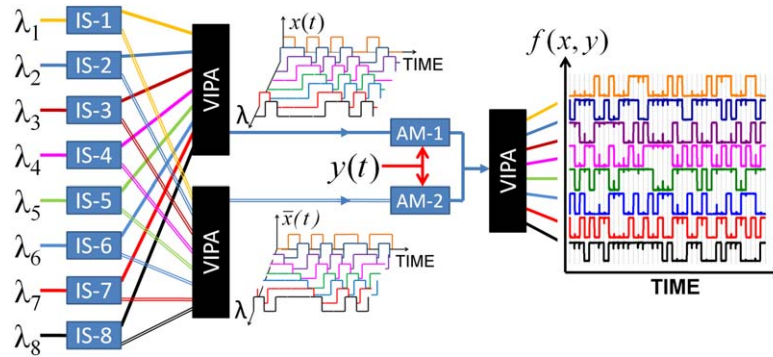


Figure 4 Proposed setup for 8 bit target pattern extraction. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

not overlap with x_{m+1} in time, the target pattern will not be detected. For an n bit long target pattern, the setup has to check all n possible relative timings between the input data and the target pattern consecutively. As a result, the experimentally demonstrated XNOR logic gate can successfully detect any target pattern assuming the input data is recorded and can be sent to the setup consecutively with controlled delay. However, the proposed setup can be modified further so that it can act on real time streaming input data instead of recorded data.

4. PATTERN EXTRACTION IN REAL TIME STREAMING DATA

The proposed multifunction optoelectronic gate operates independent of the optical signal wavelength; therefore, it can act on multiple optical bits simultaneously if they operate at different wavelengths. This is one of the advantages of our logic gate compared to other approaches (electrical or all-optical). In this pattern extraction application, this property is exploited to realize parallel processing on real time streaming data. As discussed before, to detect an n bit long target pattern, n relative delays must be checked. If all the possible delays are present at different wavelengths, the setup can detect the target pattern in real time streaming data.

Figure 4 shows the proposed logic gate that has been optimized for 8 bit long real time target pattern extraction. The 8 bit setup has eight separate wavelength channels each modulated by corresponding IS. The wavelengths have been combined by the use of a virtually imaged phase array (VIPA) filter [9]. Each wavelength carries the same input data but with an additional 1 bit time delay with respect to its neighboring channels. The required 1 bit time delay between the channels can be realized

either in the optical domain (by delaying the modulated optical signals), or in the electrical domain (by driving the IS with delayed electrical waveforms). In our experiments, we have delayed the signals in the electrical domain. As a result, the input data stream in all the possible relative timings with respect to the target waveform enter to the amplitude modulator stage together, and all of them are checked for the target pattern simultaneously. At the output, the wavelength channels are separated with another VIPA and sent to corresponding electronic counters or incorporated to optical integrators, which will check for eight consecutive “1”s synchronized with the target signal.

To experimentally demonstrate this real time data mining, a two channel version of the proposed setup has been built for detection of a 2 bit long target pattern as seen in Figure 5. In this proof-of-concept experiment, we have used two wavelengths, λ_1 and λ_2 , spaced by approximately 0.19 nm. The 2 bit long target pattern was chosen “10,” and the periodic input data were chosen to be “11100” at 50 Mbit/s. The speed of the bit pattern was limited by the electronic waveform generators. The two wavelengths have been spatially separated by the use of a VIPA and the input data is imprinted on λ_2 and its 1 bit delayed version is imprinted on λ_1 .

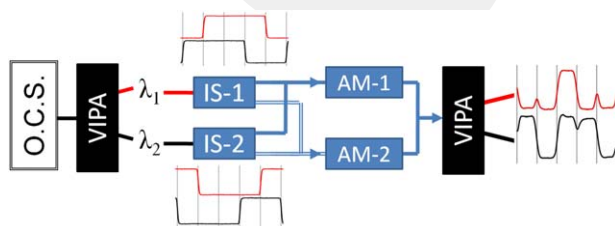


Figure 5 Experimental setup for simultaneous 2 bit target pattern extraction. O.C.S.: Optical Comb Source, VIPA: Virtually Imaged Phase Array, IS: Interferometric Switch, AM: Amplitude Modulator. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

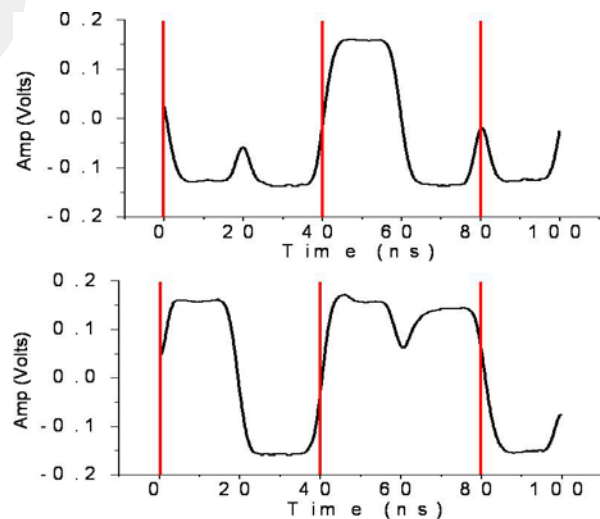


Figure 6 Output of the system for real time 2 bit pattern extraction. In the time slot, between 40 ns and 80 ns, there exist two consecutive “1” bits. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

After data imprinting, two wavelengths have been combined with a simple fiberized coupler. Both amplitude modulators process both wavelengths (i.e., both input signals) simultaneously. In other words, the system performs parallel operation on the optical bits. After the amplitude modulators, the wavelengths are separated again with a VIPA and detected simultaneously with a two channel oscilloscope used as the electronic counter. As seen in Figure 6, the channel λ_2 has two consecutive “1” bits while the other channel has not. The experimental setup has successfully detected and located the 2 bit long target pattern inside the real time streaming input data.

In our experiments, the speed limitation was due to the limited bandwidth of the electronic waveform generators. With our approach, data mining at 10's of GHz rates should be possible using commercially available components.

5. CONCLUSION

We have proposed a novel optoelectronic multifunction gate that can be dynamically configured to act as any logic gate of two variables. This proposed system is independent of wavelength and allows simultaneous parallel computing. A simplified version of the proposed setup was also experimentally demonstrated as an optoelectronic XNOR logic gate for target bit pattern extraction and data mining. The setup has successfully located and detected an 8 bit target in a prerecorded data and a 2 bit long target patterns inside a real time streaming input data without requiring any prior knowledge about the input data stream other than the data rate. The speed of the proposed setup is limited by the bandwidth of the IS and the separation of wavelength channels. With this approach, data mining at 10's of GHz rates should be possible using commercially available components. It is also possible to implement the same layout on a photonic integrated chip for improved channel number, stability, and large scale fabrication.

REFERENCES

1. N. Deng, K. Chan, C.K. Chan, and L.K. Chen, An all-optical XOR logic gate for high-speed RZ-DPSK signals by FWM in semiconductor optical amplifier, *IEEE J Sel Top Quantum Electron* 12 (2006), 702–707.
2. K.L. Hall and K.A. Rauschenbach, All-optical bit pattern generation and matching, *Electron Lett* 32 (1996), 1214–1215.
3. K.E. Chlouverakis and M.J. Adams, Optoelectronic realization of NOR logic gate using chaotic two-section lasers, *Electron Lett* 41 (2005), 359–360.
4. H. Adachi, K. Matsuda, T. Chino, and J. Shibata, InGaAsP/InP optoelectronic exclusive-OR (XOR) gate operating with optical inputs and outputs, *IEEE Photon Technol Lett* 3 (1991), 1013–1015.
5. Z. Porada and E.S. Osowska, Optoelectronic logical Gates “and”, “or” and “not”, *Active Passive Electron Compon* 27 (2004), 95–105.
6. P.B. Hansen and A.H. Gnauck, A dual-drive Ti:LiNbO₃ Mach-Zehnder modulator used as an optoelectronic logic gate for 10-Gb/s simultaneous multiplexing and modulation, *IEEE Photon Technol Lett* 4 (1992), 592–593.
7. L. Comtet, *Advanced combinatorics: The art of finite and infinite expansions*, Springer, Netherlands, 1974, p. 186.
8. N. Huang, M. Li, R. Ashrafi, L. Wang, X. Wang, J. Azaña, and N. Zhu, Active Fabry-Perot cavity for photonic temporal integrator with ultra-long operation time window, *Opt Express* 22 (2014), 3105–3116.
9. M. Shirasaki, A.N. Akhter, and C. Lin, Virtually imaged phased array with graded reflectivity, *IEEE Photon Technol Lett* 11 (1999), 1443–1445.

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ENHANCED SENSITIVITY HIGH TEMPERATURE OPTICAL FIBER FPI SENSOR CREATED WITH THE CATASTROPHIC FUSE EFFECT

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ABSTRACT: In this work, we describe a novel and cost effective approach based on optical fiber microcavities, for sensing high temperature values (up to 1150°C). The proposed sensor is produced by splicing standard single mode optical fibers with fibers destroyed by the catastrophic fuse effect, resulting in a microcavity structure in the fiber core region. These microcavities have a thermal sensitivity of $10.43 \pm 0.15 \text{ pm } ^\circ\text{C}^{-1}$, for temperatures up to 1150°C, which compares well with the sensitivity of Fabry–Perot interferometric sensing cavities but with the advantage of substantially reduced manufacturing costs. © 2015 Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 57:972–974, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28997

Key words: high temperature sensor; Fabry–Perot micro cavity; fiber fuse effect

1. INTRODUCTION

We have witness a high demand for temperature sensing systems, able to sustain its features in harsh environments at high temperature values [1]. Nowadays, the optical fiber sensors are the most promising available sensing technologies, due to its advantages over the traditional electronic devices, such as immunity to electromagnetic interferences, electrical isolation, reduced weight and volume, and durability and resistance to harsh environments [2]. Among the several optical fiber sensing technologies, the ones often used for high temperatures sensing are based on regenerated fiber Bragg grating (FBG) [3, 4] and Fabry–Perot interferometric (FPI) microcavities [5, 6]. Uniform FBG based sensors are commonly used at low temperature values, and, its use for high temperature sensing is impracticable, as the grating erases itself at temperatures above 550°C [7]. To overcome this limitation, regenerated FBG sensors were proposed, being suitable for measurements up to 1000°C, with thermal sensitivity of $\sim 16 \text{ pm } ^\circ\text{C}^{-1}$ [3]. Nevertheless, its production is a costly and time consuming process. More recently, a new emphasis was given to FPI based sensors, which require high cost production investments in complex fabrication and implementation setups [5, 6].

In this work, we present a novel and cost effective solution to produce high temperature optical fiber FPI sensors, suitable for harsh environments with large temperature gradients. The sensors are based on microcavities produced by the recycling of optical fibers destroyed by the catastrophic fuse effect [8].