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On-chip electro-optic multiplexing circuit using serial microring boxcar filters

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ABSTRACT

We propose a new variant of electro-optic multiplexing scheme using the boxcar filter arrangement. The circuits consist of multistage add-drop multiplexers that can offer external input-output connections. Input from a single light source can be fed into the system through the input port or through the free-space from light fidelity (LiFi) node. The light signal is fed into boxcar filters and the roll-off bands are obtained. The output of the circuits is formed at the drop, through and the whispering gallery mode (WGM) node of the circuit output. By using the electro-optic conversion in Si-Graphene-Au layer stack, time division (TDM), wavelength division (WDM), frequency division multiplexing (FDM) can be performed. The simulations have shown that a combination of 7 roll-off bands with the maximum spectral widths or bandwidths of ~6.09 µm or ~7.63 THz can be obtained.

Electro-optic circuits have been used in various aspects to serve the current required information capacity, in which both electronic and optical signals can be applied and used incorporating in the information networks [1–4]. Currently, the requirement of the high capacity network is heading to the 5G protocol [5,6], in which the applications of the internet of thing (IoT) [6] will be realized. Therefore, the network equipment such as filter, modulator, amplifier, multiplexer and demultiplexer are required to have the functions that can support the high capacity networks. From which the huge data information can be linked by the big data transmission line, while the network bandwidths are supported by the light fidelity (LiFi) [7] and wireless fidelity (WiFi) [8]. In this article, we propose the use of a device called boxcar filter that can be used to perform various functions to serve the network signal processing applications [9]. Each boxcar filter circuit can have an individual bandwidth (roll-off) that can be used to accommodate the signal processing in the transmission network. The train of the roll-off bands can be generated by using the serial boxcar filters as shown in Fig. 1, which can be used to accommodate the large demand for bandwidths. However, only one function in either electronic or optical technique cannot reach the target, therefore, we have proposed the use of the electro-optic conversion that can offer both types of signals. Silicon-graphene-gold layer stack is proposed to use for the electro-optic signal conversion, where the exchange between electron and light energy can be performed. Principally, the electrical mobility (µ) is given by $\mu = \frac{e\tau}{m} = \frac{ed}{mv_F}$ [10], which is a directly related to electrical conductivity, e, τ, m, d, and v_F represent electronic charge, mass of electron, mean free path and Fermi velocity of the charge carriers respectively. When the optical or electric field is applied to the input port of the system in Fig. 1. From which the electrical or optical field can be input into stacked layers via the metal contact or silicon layer. The conversion is induced within the stacked layers. The input field is presented as $E_{in} = E_Z = E_0 e^{-ik_z t - \omega t}$, where E_0, k_z, and ω are initial electric field amplitude, wave number along the z-axis (direction of propagation) and angular frequency of the wave propagation

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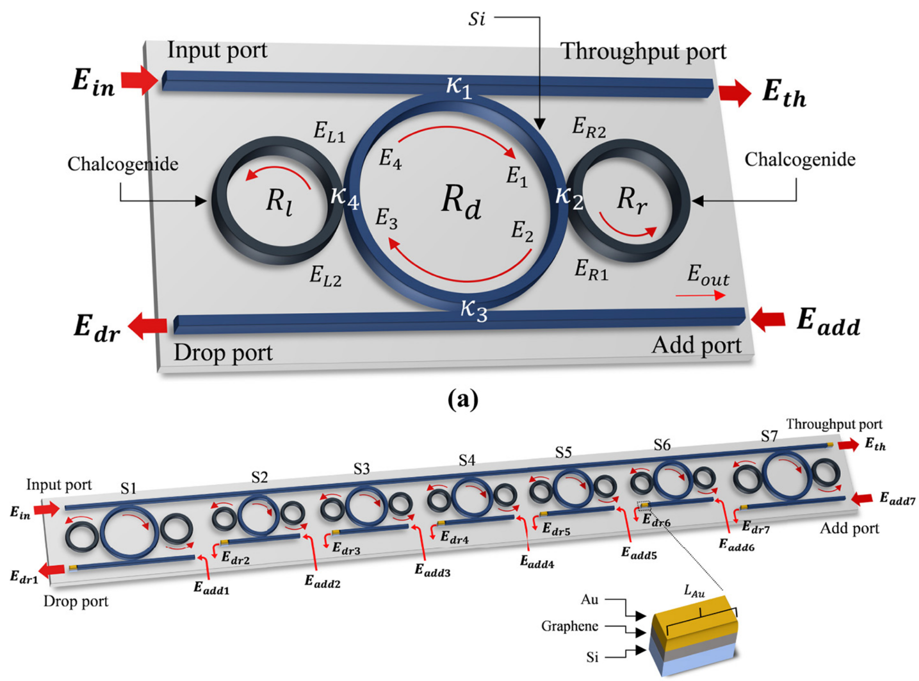

Fig. 1. A schematic model of the boxcar filters, where (a) a schematic of the on-chip Si-ChG microring circuits, (b) the proposed electro-optic multiplexing circuit, where R_l, R_r, R_d are the radii of the two side rings, left (R_l) and right (R_r) hands, and the center ring (R_d). E_{Subs} are the electrical fields in the related system.

respectively. The field propagates into the boxcar filter system, from which the output fields can be detected at the circuit through and drop ports. The system output is obtained at the last add-drop multiplexer output ports. WGM is the desired outputs at the drop and through ports. In application, the external signal processing via the add port can be applied to all boxcar circuits, while the output signals can be received from the drop ports.

For the input optical field (E_1) fields at all ports of the boxcar filter system are given by the Eqs. (1)–(7) [11,12].

$$E_{in} = E_z = E_0 e^{-ik_z t-\omega t} \tag{1}$$

$$E_{th} = \left[\frac{G.\ F^2 - G.\ F.\ C + A.\ H.\ J}{F^2.\ J - C.\ F.\ J}\right] E_{in}, E_{ad} = 0 \tag{2}$$

$$E_{th} = \left[\frac{G.\ F^2 - G.\ F.\ C + A.\ H.\ J}{F^2.\ J - C.\ F.\ J}\right] E_{in},\ \text{when}\ E_{ad} = 0 \tag{3}$$

$$E_{th(i)} = E_{in}\cdot \prod_{i=1}^{n} \left[\frac{G_i\cdot F_i^2 - G_i\cdot F_i\cdot C_i + A_i\cdot H_i\cdot J_i}{F_i^2\cdot J_i - F_i\cdot C_i\cdot J_i}\right] \tag{4}$$

$$E_{dr} = \frac{K(F-C-BL)E_{ad} - L\cdot A\cdot E_{in}}{M(F-C)} \tag{5}$$

$$E_{dr} = \frac{-L\cdot A}{M(F-C)}\cdot E_{in},\ \text{when}\ E_{ad} = 0 \tag{6}$$

$$E_{dr(i)} = E_{in}\cdot \prod_{i=1}^{n} \left[\frac{-L_i\cdot A_i}{M_i(F_i - C_i)}\right] \tag{7}$$

where the subscript i is the sequence of the micro-ring resonator which uses the individual parameter. Details of the mathematical considerations of this work can be found in the reference [13].

The boxcar filters are applied to have the roll-off trains of wavelength bands that can be used to accommodate the huge data capacity such as the big data regime, where the data capacity of 40 Penta byte is required [12]. The function of each boxcar is separated and defined by [14]

$$\Pi_{a,b}(x) = H(x-a) - H(x-b) \tag{8}$$

Which is equal to 1 for a $\leqslant x \geqslant b$ and 0 otherwise. Here h(x) is the Heaviside step function. The special case $\Pi_{-\frac{1}{2},1/2b}$ (x) gives the unit rectangle function.

In simulations, the serial add-drop multiplexers are used to form the boxcar filters as shown in Fig. 1. The initial and final ones are the input and output rings and used to form the down and link conversion of the transmitted signals, which are in the forms of the WGM beams [16]. The boxcar bands are called the roll-off bands and obtained in the forms of pulse trains with the certain guardband. The external applied sources can be connected to each boxcar filter circuit. By using the electro-optic conversion, all forms of the electro-optic multiplexing-demultiplexing signals can be connected to the network link via the device ports. From which the network capacity can be significantly increased and reached the big data scheme. Initial values for roll-off bands are obtained by using the graphical of the Optiwave program. Using these values, final simulations were performed in MATLAB.

The selected parameters are given in all related figure captions. The Optiwave program result is as shown in Fig. 2, the required output is in the form of WGM which are generated at the boxcar filter number 1 and 7, which are obtained. The used parameters are given in the figure caption. The transmission signals within the system are shown in Fig. 3, where (a) the input and through port signals, (b) the WGM outputs, and (c) the drop port signals with the output wavelength from 1.30 to 1.80 µm. The spectral width of 100 µm is achieved. The drop port outputs of the boxcar filters are also plotted in terms of the electron mobility, which can be available in both electrical and optical applications. The required port (drop port) is embedded in the stacked layer which allows the electro-optic converter application. The relationship between mobility output and the input power is shown in Fig. 4. The gold (Au) lengths are ranged from 200 to 1000 nm, the linear relationship trend between the driven electron mobility and the input power is confirmed. Fig. 5 shows the boxcar filter roll-off of S1-S7, in which the spectral width of each boxcar filter is ~8.7 nm. Similarly, the add port of each boxcar filter can be embedded by the stack layer for the external signal processing applications.

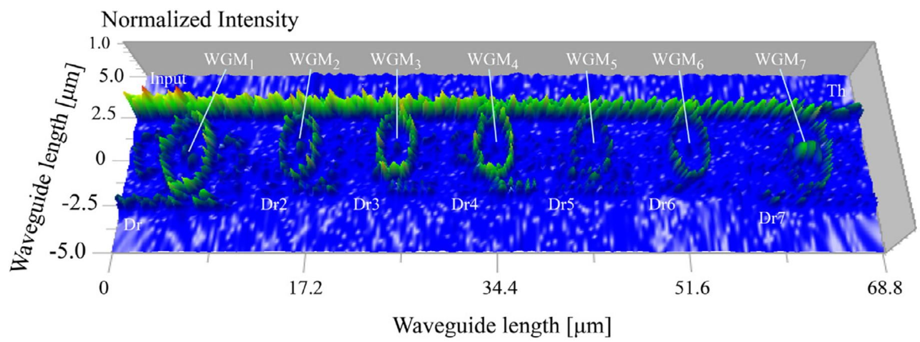

Fig. 2. The graphical results of the wave propagation in the system in Fig. 2 using the Optiwave program, where the input light source wavelength center is at 1.55 µm. The ring system S1 and S7, $R_l = R_r = 1.1$ µm, $R_d = 2.0$ µm. The ring system S2 to S6, $R_l = R_r = 0.8$ µm, $R_d = 1.6$ µm. Each of the coupling constant, κ_1 to κ_4, of all the ring system is 0.5, the refractive index; $n_{0ChG} = 2.9$, $n_{2ChG} = 1.02 \times 10^{-17}\,\mathrm{m^2\,W^{-1}}$ [15], $n_{Si} = 3.47$ (Si-Crystalline silicon).

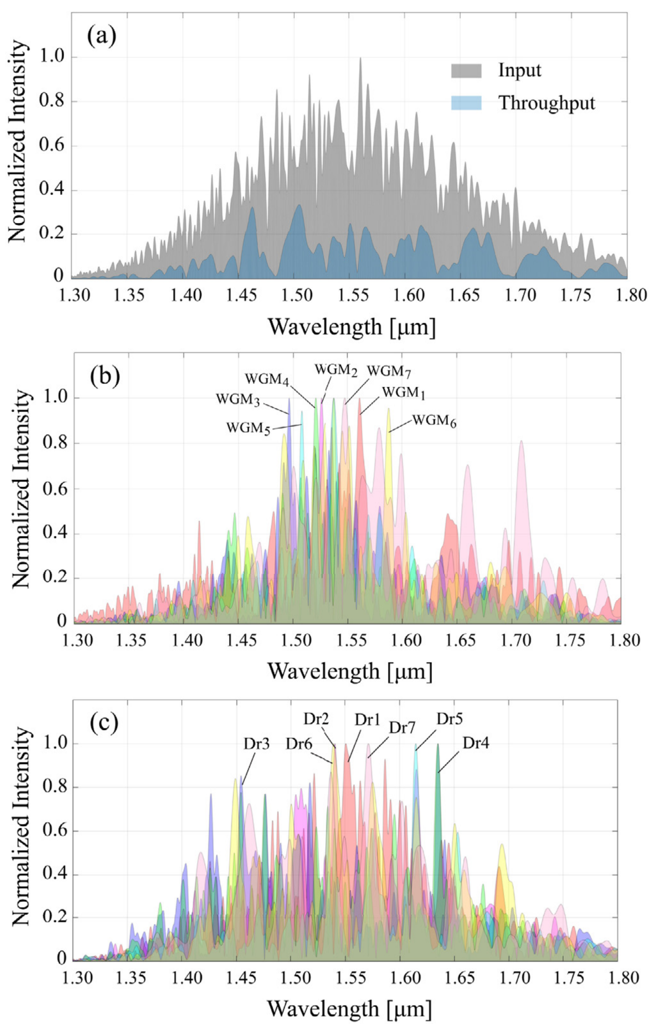

Fig. 3. Plot of the simulation results of the used parameters in Fig. 3 using the MATLAB program, where comparative results of the two-channel outputs at (a) the input and throughput ports, (b) the WGM outputs, (c) the drop ports.

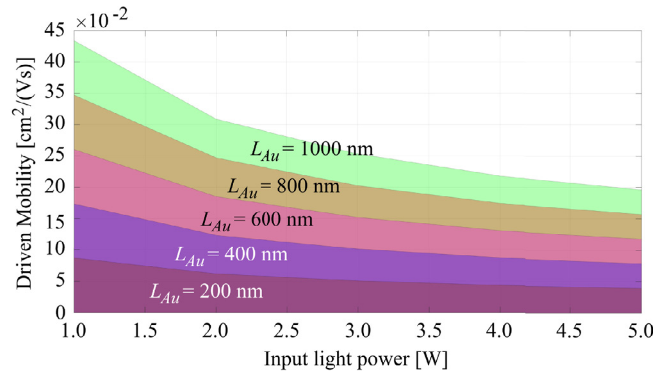

Fig. 4. Mobility output at the Dr7 port, the gold and graphene layer parameters are w = 0.5 µm, thickness = 0.2 µm. In the calculation, the electron mobility, $\mu = \frac{V_d}{E}$, where V_d is Drift velocity, which is $v_d = \frac{j_s}{nAq}$, where $j_s = \sigma E$ is the current density flowing through the material, $\sigma = 4.10 \times 10^7\,\mathrm{Sm^{-1}}$ at 20 °C is the conductivity of Au. n is the charge-carrier number density, n = [Density × free electron number per atom × Avogadro's constant × 10^6]/[Molar mass] electrons per cubic metre. For Au, the density is 19.32 $\mathrm{gcm^{-3}}$, the Avogadro's constant is 6.02×10^{23} atom, the free electron number of Au is 1, and the Molar mass of Au is 196.9665690 $\mathrm{g\,mol^{-1}}$.

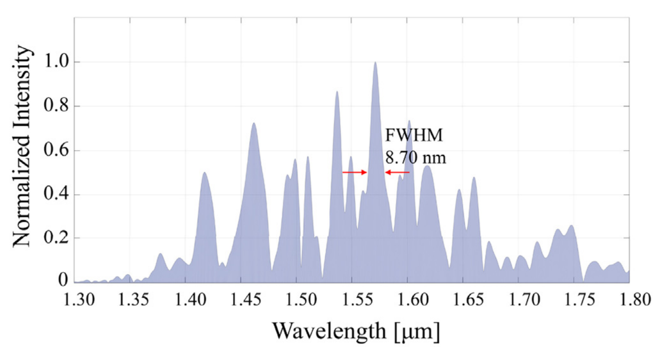

Fig. 5. The plot of the boxcar filter roll-off in terms of the spectral width at the drop port of Dr7, in which the spectral width of each boxcar filter is ~8.7 nm. The combination bandwidths of 7 boxcar roll-off bands of ~7.63 THz is obtained.

In summary, we have proposed the use of the microring boxcar filters for multi-roll-off bands of the electro-optic signals. The ChG ring resonator is used as the primary ring resonator, from which the wide bands in terms of wavelength, time and frequency have been plotted and discussed for the high capacity transmission i.e. big data. The external applications such as modulator, filter, multiplexing and demultiplexing in either electronic or optical are also available. This means that the application of the proposed circuits can be used to accommodate WDM, TDM, FDM and OFDM by applying to the boxcar filter nodes, where finally the required applied signals (electrical or optical signal) will be transmitted and received to and from the network. The combination bandwidths of 7 boxcar roll-off bands of ~7.63 THz is obtained. This is an on-chip scale circuit, which means that the increase in the boxcar filters can be applied to reach the 40 Petabyte requirement.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.rinp.2018.05.026.

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