Add/drop filters based on SiC technology for optical interconnects

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Abstract. In this paper we demonstrate an add/drop filter based on SiC technology. Tailoring of the channel bandwidth and wavelength is experimentally demonstrated. The concept is extended to implement a 1 by 4 wavelength division multiplexer with channel separation in the visible range. The device consists of a p-i(a-SiC:H)-n/p-i(a-Si:H)-n heterostructure. Several monochromatic pulsed lights, separately or in a polychromatic mixture illuminated the device. Independent tuning of each channel is performed by steady state violet bias superimposed either from the front and back sides. Results show that, front background enhances the light-to-dark sensitivity of the long and medium wavelength channels and quench strongly the others. Back violet background has the opposite behaviour. This nonlinearity provides the possibility for selective removal or addition of wavelengths. An optoelectronic model is presented and explains the light filtering properties of the add/drop filter, under different optical bias conditions.

1. Introduction
In the near future, increases in power efficiency per data bit is intended to be achieved by replacing electrical interconnects with their optical counterparts. So, in the visible range, the conception of new devices based on new materials for optically switchable multilayer photonic structures is a demand[1, 2]. A combined RGBV (red, green, blue and violet) wavelength router/switch based on SiC technology can increase, in visible range, the connectivity of an optical system and reduce the number of signal demultiplexers. Tunable backgrounds filters based on a-SiC:H multilayered devices represent a class of filters with characteristics very similar to those of microring resonators [3, 4]. Their filter characteristics make these devices particularly attractive for integrated optics or photonics applications, channel dropping filters, WDM demultiplexers, notch filters and for optical switching or optical wavelength conversion [5]. Filter applications like add/drop multiplexers will be covered in this paper.

2. Device design, characterization and operation
The wavelength add/drop filter is realized by using double pin/pin a-SiC:H photodetector sandwiched between two transparent TCO contacts and two front and back biased optical gating
elements as depicted in Figure 1.

The filter consists of a p-i'(a-SiC:H)-n/p-i(a-Si:H)-n heterostructure with low conductivity doped layers. The thicknesses and optical gap of the front i' (200 nm; 2.1 eV) and back i- (1000 nm; 1.8 eV) layers are optimized for light absorption in the blue and red ranges, respectively [6, 1].

Monochromatic pulsed lights from commercial LED’s (input channels) separately (R: 624 nm, 25 µW/cm²; G: 526 nm, 46 µW/cm²; B: 470 nm, 60 µW/cm²; V: 400 nm, 150 µW/cm²) or in a polychromatic mixture (multiplexed signal) at different bit rates illuminated the device. Independent tuning of each channel is performed by steady state violet optical bias superimposed separately from both sides and the generated photocurrent measured at -8V. The spectral sensitivity, under violet background and without it, was tested through spectral response measurements applied from both sides (Figure 2). In Figure 2a the optical bias was applied from the front side and in Figure 2b from the back side. For comparison the normalized spectral photocurrent for the front, p-i'-n, and the back, p-i-n, photodiodes (dash lines) are superimposed. Those measurements were obtained using two separate similar pin diodes produced in the same conditions as the global structure.

Data shows that the front and back diodes, separately, presents the typical responses of single p-i-n cells with intrinsic layers based on a-SiC:H or a-Si:H materials, respectively. The front diode cuts the wavelengths higher than 550 nm while the back one rejects the ones lower than 550 nm. The overall device presents an enlarged sensitivity when compared with the individual ones. Under front irradiation the sensitivity is much higher than under back irradiation. Under front irradiation the violet background enhances the spectral sensitivity mainly in the long wavelength range (>550 nm) while back irradiation strongly quenches this and enhances the short wavelength range (see arrows in both figures). Thus, back irradiation, tunes the front diode while front irradiation selects the back one.

3. Optical bias filtering effects
In Figure 3 the spectral gain (α'), defined as the ratio between the spectral photocurrents under violet illumination and without it, is plotted. The background intensity was changed between 2300µWcm⁻² and 16µWcm⁻².
Results show that under back bias the gain is high at short wavelengths and strongly lowers for wavelengths higher than 500 nm, acting as a short-pass filter. Under violet front light the device works as a long-pass filter for wavelengths higher than 500 nm, blocking the shorter wavelengths. So, by switching the irradiation side the short-, and long- spectral region can be sequentially tuned. The medium region (475 nm-530 nm) can only be tuned by using both active filters. A trade-off between the background side and intensity has to be established. Under front illumination the reddish part of the spectrum is enhanced with the intensity while under back illumination the main enhancement occurs at the violet-blue region.

Four monochromatic pulsed lights separately (red, green, blue and violet input channels, Figure 4) or combined (multiplexed signal; Figures 5 and 6) illuminated the device at 12000 bps. Steady state violet bias was superimposed separately from the front (a) and the back (b) sides and the photocurrent was measured. In Figure 4, the transient signals were normalized to their values without background and, for each individual channel, the mean values of the optical gains added.

Results show that, even under transient conditions and using commercial LED the background side alters, in a different way, the signal magnitude of the input channels. This non-linearity provides the possibility for selective removal or addition of wavelengths.

As expected from Figure 3, under front irradiation it enhances mainly the spectral sensitivity in the medium-long wavelength ranges ($\alpha_R^{\text{V}}=7.3$, $\alpha_G^{\text{V}}=3.2$). Violet radiation is absorbed at the top of the front diode (Figure 1), increasing the electric field at the back diode [2] where the red and part of the green incoming photons are absorbed. Under back irradiation the electric field increases mainly near the front p-i-n interface where the violet and part of the blue incoming channels generate most of the photocarriers ($\alpha_V^{\text{V}}=15$, $\alpha_B^{\text{V}}=1.9$). So, by switching between front to back irradiation the photonic function is modified from a long- to a short-pass filter allowing, alternately selecting the red or the violet channels. The implementation of a wavelength division multiplexer requires that the channel wavelength may be tailored such that add/drop filters with different spectral locations, may be
cascaded. Here, tailoring the filter wavelength is achieved by changing the violet background from the front to the back side. The MUX signals due to the combination of the input channels of Figure 4 (R, G, B, V) are displayed without and under front (Figure 5) and back (Figure 6) violet irradiations. On the top the signals used to drive the input channels are displayed showing the presence of all possible sixteen on/off states. To show the backgrounds add/drop filter effect, in Figure 5 the RGB and in Figure 6 the VBG combined multiplexed signal are shown. Results show that the device is a two tunable background connected filter and acts as a wavelength selective switch. Without applied background (dark) sixteen output levels are observed each one correspondent to a one of the possible 4-channel on/off configurations (16-to-1 multiplexer).

Under applied optical bias, the side of background affects the form and the magnitude of the MUX signal in opposite ways. Under front irradiation the violet channels quenches, and so, the difference between the multiplex signals with and without the violet channel on is irrelevant. This means that under front irradiation the transmission of the violet channel changes from high to low and so, the output signal has only eight separate levels (horizontal dot lines) that can be assigned to the $2^3$ on/off possible states of an 8-to-1 RGB multiplexer. The levels are weighted by the optical gains of each channel ($\alpha^V$, Figure 4), so, the selection index for this 8-element look-up table (in the right side of Figure 5) is a 3-bit binary [RGB] code. The violet channel was switched to the drop port and the others continue in the transmission line. Under back irradiation the magnitude of the red and green channels are strongly reduced. The 8-to-1 look up table (dot lines) is clear and the 3-assigned bit binary [VBG] code displayed in the right side of Figure 6. So, the quench of the red channel allows it drops to the drop port and the others continue in the transmission line. Similar explanation could be done with the quenching of the green channel resulting in a similar [VBR] code. So, by using the add/drop SiC based filter a usable portion of the optical visible spectrum can be partitioned into wavelength bands to make signal separation possible at the receivers. The advantage of optic background tuning lies in its structural simplicity. The front background selects the red channel and drops the violet while the back background adds the violet and drops the red or the green. It provides a low-cost solution in optical and optoelectronic interconnection technologies according to their suitability of adoption in optical cross connections, switches and routers.
4. Coder/decoder device
The add/drop filter concept is extended to implement a 1 by 4 WDM. Results have shown that under front or back irradiation, each of the four channels, in turn, is enhanced or quenched. The logic MUX function is converted into a logic filter function and each channel can be decoded as a data signal to be routed to a selected destination. Figure 7 displays the normalized MUX signals due to the combination of the input channels of Figure 4. On the top, the signals used to drive the input channels are shown.

Under front irradiation, the $2^4$ levels are detected (horizontal dot lines) and grouped into two main classes due to the high amplification of the red channel (Figure 4a). The upper eight ($2^3$) levels are ascribed to the presence of the red channel ($R=1$), and the lower eight to its absence ($R=0$), allowing the red channel decoder (8-to-1 multiplexer; long-pass filter function). Since under front irradiation the green channel is also amplified the four ($2^2$) highest levels, in both classes, are ascribed to the presence of the green channel ($G=1$) and the four lower ones to its lack ($G=0$). The blue channel is slightly amplified, so, in each group of 4 entries, two subclasses ($2^1$) can be found: the two higher levels correspond to the presence of the blue channel ($B=1$) and the two lowers to its absence ($B=0$). Finally, each group of 2 entries have two very near sublevels, the higher where the violet channels is ON ($V=1$) and the lower where it is missing ($V=0$). Under back irradiation, the violet channel is strongly enhanced, the blue channel slightly and the green and red reduced (Figure 4b). The encoded multiplexed signal also has sixteen sublevels but ordered in a different way. Two classes are observed, one composed by the eight higher levels, where the violet channel is ON ($V=1$) and the other including the eight lower levels where it is OFF ($V=0$) (8-to-1 multiplexer; short-pass filter function) allowing the violet channel decoder (see bottom of Figure 7). Each group the eight levels can still be grouped in two classes of four levels each, with and without the blue channel ON. Taking into account Figure 6, those four near sublevels are ordered. The higher has both red and green channels ON, the lower both OFF and in-between only one of them is missing, the red or the green.

So, the multiplexer select code, under front irradiation, represents an address, $RGBV$, into the ordered inputs while under back irradiation it will be of the form $VBRG$. We may view those 16-element look-up tables, as consisting of two look-ups, one to select the proper group of 8, and pick the red under front irradiation or the violet under back background. Each group of 8 inputs requires 3 bits for picking the proper group of 8 and for specifying an input. By using both look-up tables any multiplex signal can be decoded.

5. Optoelectronic model
Based on the experimental results and device configuration an optoelectronic model, made out of a short- and a long-pass filter was developed [2]. In Figure 8a the ac equivalent circuit and the block diagram of the optoelectronic state model are displayed. In Figure 8b the linearized state equations are shown. The use of amplifying elements ($Q_1, Q_2$), with resistors ($R_1, R_2$) and capacitors ($C_1, C_2$) in their feedback loops, synthesize the desired filter characteristics with $\alpha_{R,G,B,V}$ the optical gain.

The input signals, $\lambda_{R,G,B,V}$ model the color channels and $i(t)$ the output signal. The amplifying elements, $\alpha_1$ and $\alpha_2$ are related with the optical gains and provide gain if needed or attenuate unwanted wavelengths. The control matrix takes into account the enhancement or quenching of the channels...
(Figure 4) due to the steady state irradiation. Under front irradiation: $\alpha_2 >> \alpha_1$ and under back irradiation $\alpha_1 >> \alpha_2$. This affects the reverse photo capacitances, $(\alpha_{1,2}/C_{1,2})$ that determine the influence of the system input on the state change (control matrix).

\[ \frac{dV_{1,2}}{dt} = \sum \left[ \frac{\alpha_i(\alpha_{i,B,GA})}{C_i} \right] i_{1,2}(t) + \left[ \frac{1}{R_i C_1} \frac{1}{R_i C_2} \right] v_{1,2}(t) \]

\[ \frac{dV_{1,2}}{dt} = \left[ \frac{1}{R_i C_1} \frac{1}{R_i C_2} \right] \sum i_{1,2}(t) \]

\[ \left[ 0 \right] \frac{1}{R_2} v_{1,2}(t) \]

\[ \begin{array}{c}
\alpha_{i,1,2} \\
1/R_1 C_1 \\
1/R_1 C_2 \\
\end{array} \]

\[ \begin{array}{c}
\alpha_{i,2} \\
1/R_2 C_2 \\
\end{array} \]

\[ \begin{array}{c}
\alpha_{i,1} \\
1/R_2 C_2 \\
\end{array} \]

\[ \begin{array}{c}
\alpha_{i,1} \\
1/R_1 C_1 \\
\end{array} \]

Figure 8. a) Block diagram and $ac$ equivalent circuit. b) Linearized state equations.

The opto-electrical model with light biasing control has proven to be a good tool to design SiC multilayer add/drop filters. Furthermore, this model allows for extracting experimental parameters by fitting the model to the measured data.

6. Conclusions
An add/drop filter based on a-SiC:H technology was analyzed. Spectral response measurements were presented.

Results have been shown that tailoring the filter wavelength was achieved by applying a 400 nm steady state optical bias either from the front or from the back sides. The add/drop filter concept was extended to implement a 1 by 4 WDM. Under front or back irradiation, each of the four channels, in turn, is enhanced or quenched. The logic MUX function was converted into a logic filter function and each channel decoded as a data signal to be routed to a selected destination.

An optoelectronic model was present and explains the add/drop filtering properties. The optoelectrical model has proven to be a good tool to design SiC multilayer add/drop filters.

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