

Evaluation of SiGe multiple quantum well modulators for short-reach, dense wavelength division multiplexed optical interconnects

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Abstract: By modeling temperature-dependent SiGe MQW electroabsorption, we calculate the number of allowed DWDM channels as a function of operating temperature, applied voltage, and a figure of merit related to the laser power penalty. We find that 20 to 40 DWDM channels at 100 GHz and 50 GHz channel spacing is possible in DWDM links with a $\sim 12^\circ$ temperature range with less than a 1 dB laser power penalty compared to the optimum single channel, single temperature case. The same number of channels can be supported over a 37° temperature range with a 3 dB power penalty.

Silicon microring and microdisk resonators offer a way to use the weak but broadband free-carrier (FC) absorption and refraction in silicon to build modulators and switches for dense wavelength division multiplexed systems (DWDM)[1]. However, the narrow optical response of resonators also makes them sensitive to small variations in fabrication, optical power levels, and operating temperature. While several techniques have been demonstrated that address the fabrication and temperature sensitivity [2,3], they have yet to be proven in large-scale, high-performance computing systems where silicon photonics is envisioned to be principally deployed.

An alternative is to use modulators that make use of the Quantum Confined Stark Effect (QCSE) discovered in the III-V material system in the 1980's [4] and recently in SiGe multiple quantum wells [5]. Modulators relying on the QCSE do not need resonators for their operation and are more tolerant to temperature and fabrication variations. However, because the QCSE is relatively narrowband (10-20 nm), they are not normally considered for use in DWDM interconnects. Here we evaluate the use of SiGe MQW modulators for use in DWDM optical interconnects. The evaluation metric is the output figure of merit (FOM) as a function of temperature and optical frequency (wavelength) that is directly (inversely) proportional to the required laser power in a link.

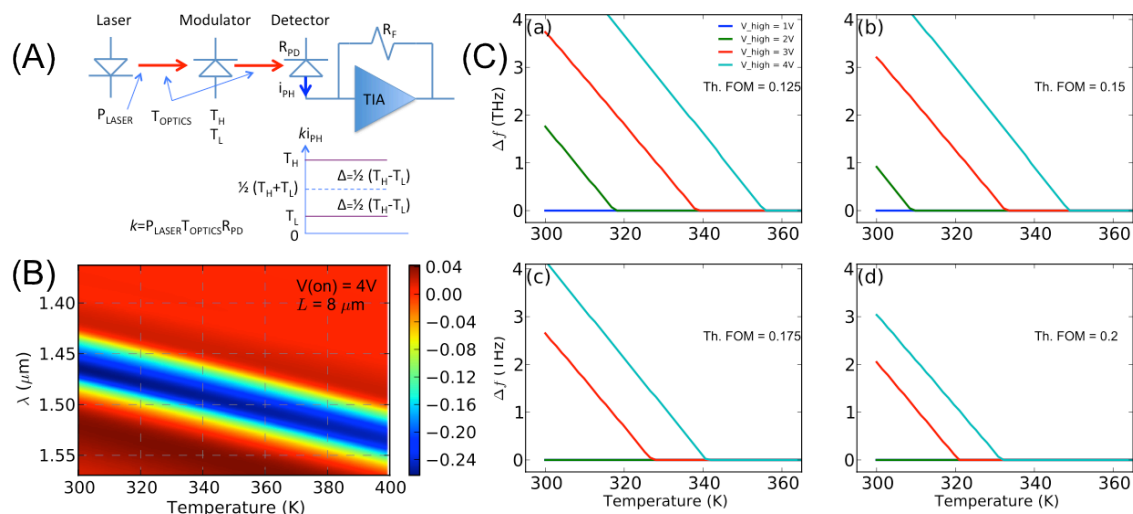


Figure 1. (A) Schematic of an optical interconnect. (B) Calculated FOM as a function of wavelength and temperature for on-state voltage of 4V and 8 micrometer device length. (C) The number of allowed DWDM channels as a function of temperature for various cutoff FOM values and on-state voltages.

We developed a model of SiGe electroabsorption by fitting the published experimental room-temperature absorption data published in [5]. We extended this model to higher temperatures by modeling the temperature-induced bandgap and exciton broadening effects. The FOM, defined as half the difference between high-state and low-state transmission, is calculated from electroabsorption values from the model and by choosing device length and ON/OFF voltages.

Figure 1(A) shows the schematic of the optical link used to model the interconnection and derive the FOM. Figure 1(B) is the calculated map of the FOM as a function of wavelength and temperature. From Figure 1(B) we can extract the number of channels that can be supported on this link for given values of power penalty and desired operating temperature range. We pick the threshold values of FOM and locate the two frequency points at which these values are attained. The difference between these frequencies defines the operating bandwidth, which directly yields the number of DWDM channels once the channel spacing is chosen. The operating bandwidth calculated using this procedure is plotted in Figures 1(C-a)-(C-d). The modulator length is fixed at 5 micrometers and the ON-state voltage ($1 < V_{ON} < 4$) and the threshold FOM (Th. FOM = 0.125, 0.15, 0.175, 0.20) are varied as shown in the figure labels.

Figures 1(C) evidences some fairly obvious trade-offs. Greater allowable operating temperature variation leads to a reduced number of DWDM channels. Reduced ON-state voltage (reduced modulator energy) also leads to reduced number of channels. We can also summarize a few data points:

1. The MQW modulator cannot effectively be used in DWDM systems without temperature control over very large ($> 60^\circ \text{C}$) temperature ranges.
2. If we constrain the temperature variation to a rather large 37°C , we can potentially have ~ 2 THz of optical bandwidth, meaning 20 to 40 channels at 100 or 50 GHz channels spacing respectively with a power penalty of 3 dB compared to the optimum single wavelength and temperature case.
3. If we constrain the temperature further to about $\sim 12^\circ \text{C}$, we can then have the 20-40 channels for a figure of merit of 0.2; that figure of merit is about equal to what can be done with silicon photonics modulators with active temperature control to $\pm 0.2^\circ \text{C}$.

Our analysis ignores the charging/discharging energy of the modulator as an optimization parameter. While it is not difficult to add this capacitive term to our model, we believe that modulator charging energy is likely to be a small percentage of the total interconnect energy, which is likely to be dominated by the laser energy. A thorough description of the modulator energy consumption is described in [6]. Throughout our analysis, we have used absorption values for surface-normal, 100% confinement structures. We expect the results to differ slightly for waveguide modulators due to $< 100\%$ confinement factor. However, the main conclusions are likely to be unchanged for a waveguide geometry.

In summary, our preliminary evaluation shows potential for a common SiGe MQW modulator design to be used in a DWDM system with a modest (20-40) number of channels provided a modest ($\sim 12^\circ \text{C}$) temperature control is provided, with the same number of channels operating over 37°C with 3dB laser power penalty compared to the optimum single wavelength and temperature case.

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References

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