



















where  $\Delta n_{eff} = n_{eff}(\omega_0) - n_{eff}(\omega_2)$ . We note that Eq. (5) is an implicit non-linear equation due to the waveguide dispersion and dispersion modification due to tight bending of the waveguides. The maximum number of channels that can be packed in a WDM system using micro-rings of radii  $r + \delta r_k$  with uniformly spaced channels at frequency spacing  $\delta\omega$  is given by:

$$k = \frac{\Delta\omega}{\delta\omega} = \frac{1}{\delta\omega} \left( \frac{c}{m_{eff}(\omega_2)} - \frac{\Delta n_{eff}}{n_{eff}(\omega_2)} \omega_2 \right) \quad (6)$$

where floor( $k$ ) is the number of channels. For example, with an available FSR of 5000 GHz and a channel spacing of 100 GHz, 50 micro-ring modulators of 2.0  $\mu\text{m}$  radius can be accommodated to provide a total bandwidth capability exceeding 500 Gbit/s.

### 6.3 Interconnect Bandwidth Density

The interconnect bandwidth density using WDM modulated signals with  $k$  wavelength channels with each channel modulated at bit rate  $B$  can be written as:

$$\beta = \frac{kB}{p} = \frac{kB}{0.12 \log_e \left( \frac{56.6z}{\pi} \right)} \quad (7)$$

where, the pitch of the silicon waveguide array  $p$ , (in microns) is related to cross talk distance  $z$  (in microns) as,

$$p = 0.12 \log_e \left( \frac{56.6z}{\pi} \right) \quad (8)$$

where  $\beta$  is the interconnect density in bits/s. $\mu\text{m}$ ,  $p$  (in microns) is the waveguide center to center pitch calculated for 250 nm X 450 nm waveguides such that a 3 dB coupling to the closest waveguide takes place for TE mode over a length of  $z$  (in microns). For example, ultra large interconnect bandwidth densities  $\sim 200$  Gbit/s.  $\mu\text{m}$  can be achieved with 25 WDM channels operating at 12.5 Gbit/s with a 3dB coupling distance of 4 cm. One can see that a considerable design space is available using silicon micro-ring modulators to scale the modulation bandwidths & interconnect densities for future interconnect applications.

## 7. Conclusion

In conclusion, we show 50 Gbit/s modulation capability using silicon micro-ring carrier injection modulators. The high speed modulation capability is enabled by engineering the carrier dynamics and extending the capability using multiple wavelengths. We show large interconnect bandwidth density of 33.3 Gbit/s. $\mu\text{m}$  and modulation bandwidth density  $> 100$  Tbit/s. $\text{mm}^2$ , both are critical figures of merit for optical networks on chip. We also discussed key design considerations for WDM systems to enable ultra large bandwidth interconnects. Scalable modulation methods based on micro-rings with novel device improvements [46–48] may meet the requirements of on-chip/chip-chip optical networks [1–8].

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