

# Error-Free Transmission of DPSK at 5 Gb/s Using a Silicon Microring Modulator

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**Abstract:** We demonstrate the first error-free transmission of DPSK using a microring modulator, with a power penalty of 1.1 dB in comparison to a commercial LiNbO<sub>3</sub> phase modulator. Additionally, long-haul transmission of microring-modulated DPSK is characterized.

**OCIS codes:** (060.5060) Phase modulation; (200.4650) Optical Interconnects; (130.4110) Modulators.

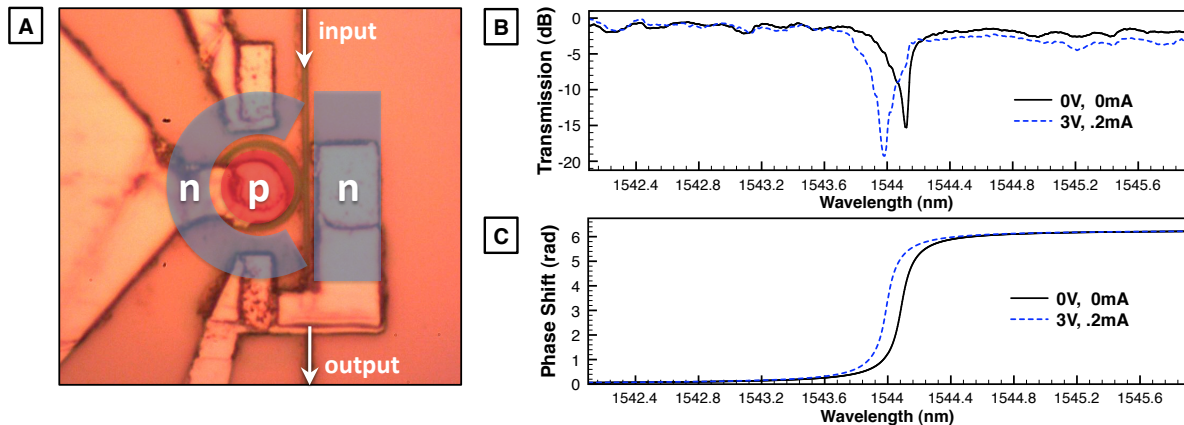
## 1. Introduction

Phase modulation provides a beneficial alternative to the traditional amplitude modulation found in optical communication systems. Differential-phase-shift-keyed (DPSK) modulation, when compared to on-off-keyed (OOK) modulation, can provide a 3-dB gain in sensitivity (when using balanced detection) as well as increased resilience against non-linear effects [1]. The trend of growing bandwidth consumption in fiber-optic networks led first to the emergence of wavelength-division-multiplexed (WDM) systems, and now to the consideration of advanced modulation formats such as DPSK and other phase-intensive formats [2].

In recent years, the technology of optical communications has been brought forth for consideration in the world of microelectronics, where the field of nanophotonics is promising to quell the bandwidth bottleneck facing multi-core processors. To ensure successful integration with existing microelectronic technology, nanophotonic components must meet the requirements for CMOS-compatibility and small footprint size. Under this rubric, the silicon microring modulator has emerged as the premier candidate for photonic networks-on-chip (NoC) due to its CMOS-compatibility, small size, and ability to be easily cascaded for WDM operation [3,4].

$$\frac{\mathbf{E}_{\text{out}}}{\mathbf{E}_{\text{in}}} = \frac{-\alpha + t e^{\left(\frac{-2\pi L i}{\lambda}\right)}}{-\alpha t + e^{\left(\frac{-2\pi L i}{\lambda}\right)}} \quad (1)$$

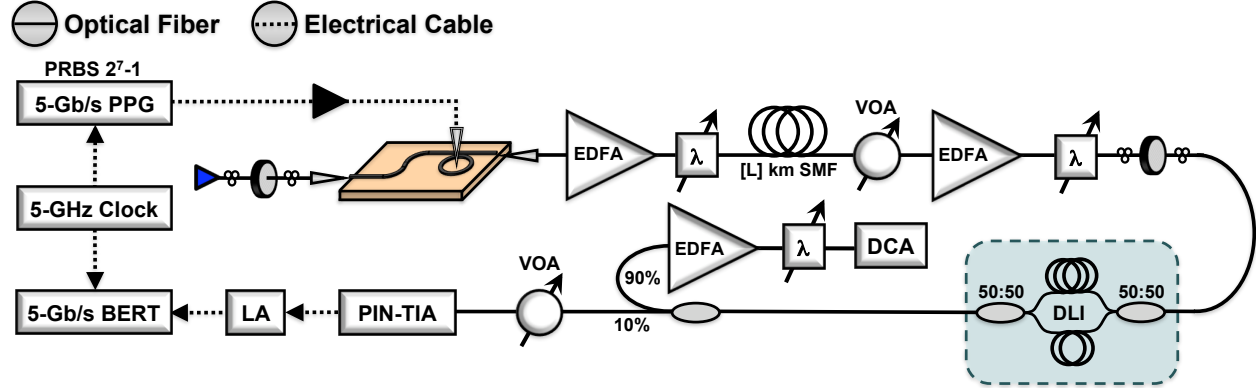
The optical response of a microring is described by equation (1), where  $L$  is the optical length of the microring,  $\alpha$  is the loss in the cavity, and  $t$  is the transmission coefficient [5]. In a silicon microring modulator, a p-i-n junction is used to alter the optical response of the structure (Fig. 1a). An electrical signal is used to pump carriers into and out of the microring, modulating the refractive index through a free carrier dispersion effect, and leading to a modulation of the transmission spectrum as seen in Fig. 1b. This mechanism is traditionally used to provide the amplitude modulation needed for OOK transmission. For over-coupled microrings, for which  $t < \alpha$ , there also exists a strong localized phase response. In Fig. 1c, the phase response is fitted using equation (1) and the transmission spectrum from Fig. 1b. It has been demonstrated theoretically [6], and only recently experimentally [7], that the modulation of the phase response can be used for DPSK transmission. Here, we demonstrate three aspects of microring-modulated DPSK necessary for its incorporation in photonic NoCs: a commercially viable data rate, error-free operation, and resilience to the errant effects of chromatic dispersion.



**Figure [1]:** (a) Microscope image of the microring modulator and its corresponding (b) amplitude and (c) phase response.

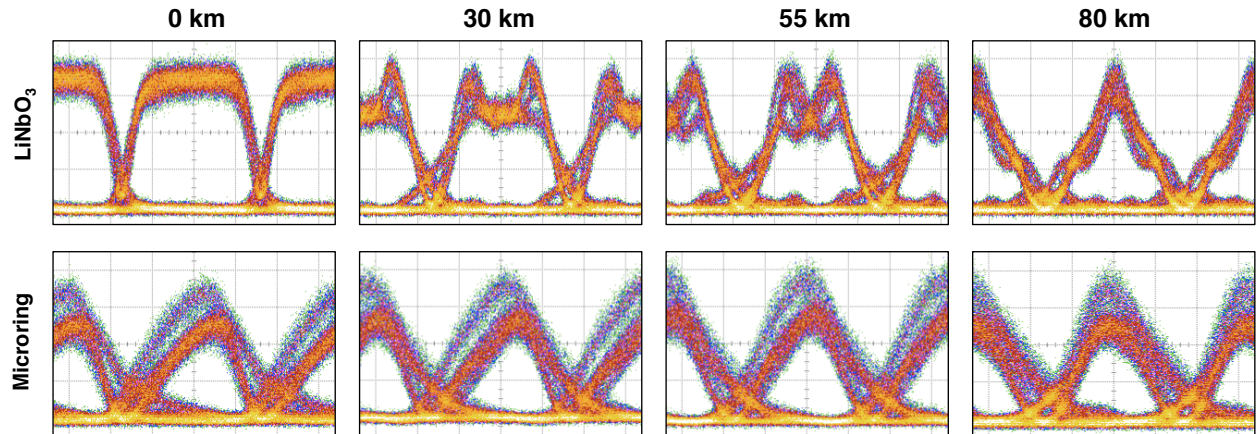
## 2. Experiments and Results

The 5- $\mu\text{m}$ -radius microring modulator used in this experiment was fabricated at the Cornell Nanofabrication Facility. The waveguide was designed for quasi-TE operation with a width and height of 450 nm and 200 nm. A surrounding Si slab of 50 nm was used for the doping. Further details on the fabrication process are found in [3].



**Figure [2]:** Experimental setup

In our experimental setup (Fig. [2]), a pulsed-pattern generator (PPG) was used to generate a 5-Gb/s non-return-to-zero (NRZ)  $2^7-1$  pseudo-random bit sequence (PRBS) electrical signal. The  $1-V_{pp}$  signal was biased at 1.2 V and conditioned with a pre-emphasis circuit to enable high speed operation of the modulator [3]. A CW tunable laser at a wavelength of 1544 nm was set to a TE polarization before being launched onto the chip with a power of 12 dBm. The microring-modulated DPSK signal egressing from the chip was amplified with an erbium-doped fiber amplifier (EDFA), and filtered ( $\lambda$ ), before being passed into  $\{0, 30, 55, 80\}$  km of single-mode fiber (SMF) at a power of 11 dBm. The varying lengths of fiber result in variable amounts of accrued loss; hence, a variable optical attenuator (VOA) was used to attenuate the signal to a fixed power of -17 dBm, ensuring consistency between measurements. This signal was then amplified and filtered before being passed into a thermally stabilized delay line interferometer (DLI) to demodulate the DPSK signal. The demodulated signal was received using a PIN-TIA photodetector followed by a limiting amplifier (LA) and fed to a bit-error-rate tester (BERT) for BER measurements. In addition, a digital communications analyzer (DCA) was used to record eye diagrams. For the back-to-back comparison, we bypassed the chip and used a commercial  $\text{LiNbO}_3$  phase modulator (rated for up to 10-Gb/s operation).

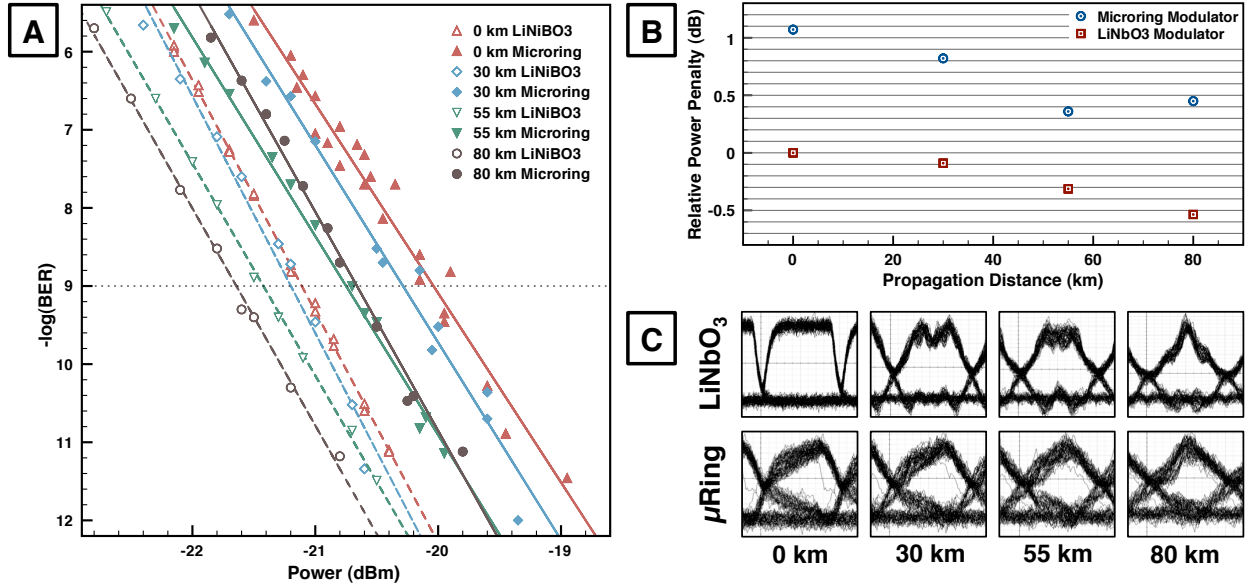


**Figure [3]:** Eye diagrams of the demodulated DPSK signal from the  $\text{LiNbO}_3$  modulator (top row) and microring modulator (bottom row) after propagating 0, 30, 55, and 80 km and passing through the DLI.

Fig. 3 depicts the eye diagrams for the demodulated signal, following its propagation through progressively increasing distances of SMF. In the eye diagrams, the shape of the microring-modulated signal is inherently different from that of the  $\text{LiNbO}_3$ -modulated signal due to the amplitude carving nature of microring resonance. While both signals incur chirp from the modulation process, the amplitude carving of the microring-modulation has the added benefit of suppressing the high-chirp transition region between bits [6]. As a result of the chirp, both signals undergo a deformation as they propagate; in this case, a transition towards RZ-type pulses is evident. This

phenomenon is verified through the numerical simulations presented in Fig. 4c, with the behavior of the microring having been modeled with equation (1).

BER curves are presented in Fig. 4a, and power penalties (taken at a BER of  $10^{-9}$ ) are summarized in Fig. 4b, where the power penalties are taken relative to the 0-km propagation of the LiNbO<sub>3</sub>-modulated signal. For both signals, the aforementioned chirp-induced transition to RZ results in negative power penalties relative to 0-km propagation [8]. The power penalty between the microring-modulated signal and LiNbO<sub>3</sub>-modulated signal varies from a high of 1.1 dB at 0-km of propagation, to a low of .7 dB at 55-km of propagation. The power penalties of the microring-modulated signal are consistent with a theoretical study of microring-modulated DPSK propagation in [9], with the aforementioned study reporting progressively more negative power penalties up to a bandwidth product of 225 Gb-km/s (45 km at 5 Gb/s).



**Figure [4]:** (a) BER curves. (b) Power penalties taken relative to 0-km propagation of the LiNbO<sub>3</sub>-modulated signal. (c) Numerical simulations of the LiNbO<sub>3</sub>-modulated (top row) and microring-modulated (bottom row) signals.

#### 4. Conclusions

Error-free operation (defined as a BER of  $10^{-12}$ ) at a propagation of 80 km was verified for microring-modulated DPSK. Furthermore, it has been shown that a microring modulator can produce error-free DPSK modulation at speeds and power penalties competitive with a commercial LiNbO<sub>3</sub> modulator. Additionally, the resilience of the microring-modulated DPSK to the effects of dispersion has been demonstrated through the negative power penalty incurred at a bandwidth-distance product of 400 Gb-km/s. This validates the use of microring-modulated DPSK for either long-haul transmission, or photonic NoCs, where highly dispersive elements (such as slow light buffers) emulate the dispersion found in long-haul transmission. Finally we note that while, in this experiment, a CMOS-compatible crystalline-Si microring modulator was used, the results are generalizable to any material system, such as deposited Si, Si<sub>3</sub>N<sub>4</sub>, polymers, or III-Vs.

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