

# 40-Gb/s colorless tunable dispersion compensator with 1000-ps/nm tuning range employing a planar lightwave circuit and a deformable mirror

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**Abstract:** We propose and demonstrate a tunable dispersion compensator for 40-Gb/s signals consisting of a waveguide grating router and a deformable mirror. It has an adjustment range of  $\pm 500$  ps/nm and a 100-GHz free-spectral range.

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## 1. Introduction

An optical tunable dispersion compensator (TDC) is essential for 40-Gb/s long-reach links. Fiber temperature changes in long links are enough to require the use of a TDC, and electronic dispersion compensation at 40 Gb/s is too immature. The TDC needs to be colorless, meaning that it has a free-spectral range (FSR) equal to the channel spacing, enabling reconfigurable wavelength-division multiplexing (WDM) networks and reducing inventory. Bulk-optic<sup>[1,2,3,4]</sup>, ring-resonator<sup>[5]</sup>, waveguide-grating router (WGR)<sup>[6]</sup>, and Mach-Zehnder interferometer<sup>[7,8]</sup> colorless TDC's have been demonstrated. Other desirable TDC features include a fast tuning speed, single-knob dispersion adjustment, low power consumption, and small size.

The WGR-based TDC is colorless, has fast tuning, has single-knob adjustment, is bandwidth efficient, can provide a very large tuning range, and is compact. Here we present a WGR-based TDC that uses a deformable mirror rather than a thermo-optic lens<sup>[6]</sup>, saving significant power consumption and size. We note that a non-tunable dispersion compensator using a WGR and a fixed mirror was previously demonstrated<sup>[9]</sup>. Our WGR has an extremely high spectral resolution, and with it we demonstrate 1000 ps/nm tuning range, the largest reported for a 40-Gb/s 100-GHz-FSR TDC, to our knowledge. Ref. [10] does present a 40-Gb/s TDC with 1600 ps/nm tuning range, but it had a 200-GHz FSR, requiring two codes to cover all WDM channels. Ours is also the first demonstration of a polarization-independent WGR-based TDC without using polarization diversity.

## 2. Design

The waveguide layout and concept of the TDC are shown in Fig. 1. Light enters a planar lightwave circuit (PLC) containing an extremely high resolution WGR through the "I/O" waveguide is spectrally spread out across a variable curvature reflecting membrane. There is a plano-cylindrical glass lens (1-mm radius) attached to the PLC that collimates the light in the plane of the PLC. To achieve chromatic dispersion, one must apply a phase distribution that varies quadratically with wavelength. The membrane changes the amount of dispersion by changing its curvature, which it does by buckling. The closer the two ends holding the membrane are brought to each other, the more the curvature.

Using a buckling mirror is possible because the WGR star coupler radius,  $R_0$ , is chosen such that only one sign of curvature of the mirror,  $R$ , is required to tune the full dispersion range. One can understand this from the following equation for the dispersion of the apparatus (neglecting the index difference between glass and air):

$$D = -\frac{2n\lambda_0}{c_0} \left( \frac{R - R_0}{RR_0} \right) \left( \frac{dx}{d\lambda} \right)^2 \quad (1)$$

where  $n$  is the refractive index,  $\lambda_0$  is the free-space wavelength,  $c_0$  is the free-space speed of light and  $dx/d\lambda$  is the spatial dispersion,

$$\frac{dx}{d\lambda} = \frac{c_0 R_0}{na\Delta f\lambda_0} \quad (2)$$

$a$  is the grating-arm pitch at the star coupler, and  $\Delta f$  is the WGR free-spectral range. In our case,  $R_0 = 3.0$  mm,  $a = 11.5$   $\mu$ m, and  $\Delta f = 100$  GHz.

As one can see, the WGR is “pinched” in the middle<sup>[11]</sup>. The pinching 1) gives significant savings in consumed wafer area, 2) significantly reduces the grating sensitivity to refractive index gradients in the wafer by occupying a smaller extent, and 3) enables the insertion of a small half-wave plate to make the TDC polarization-independent (the WGR is perfectly symmetric about its center line). The WGR has 34 grating arms. Despite the pinching, such a high resolution WGR is still expected to have significant fabrication-induced phase errors. The phase errors can be divided into linear, quadratic, and higher-order distributions across the grating arms. One significant advantage of our design is that the linear component is compensated by adjusting the WGR temperature, and the quadratic component is compensated by adjusting the focal position of the deformable mirror when the device is put together.

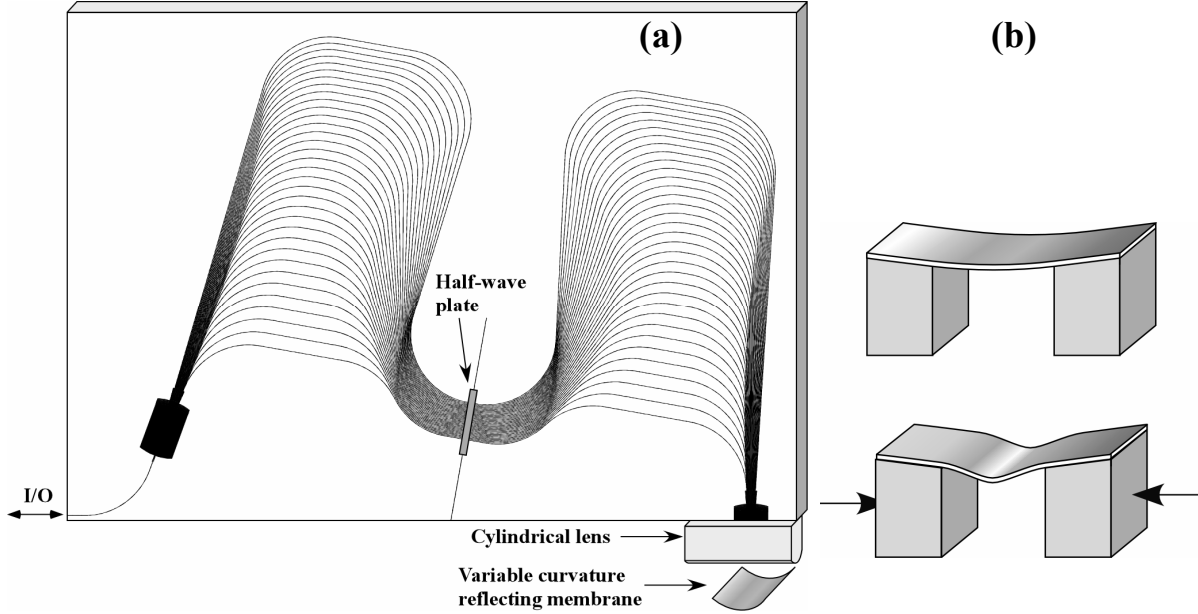


Fig. 1. (a) Waveguide layout and concept of the tunable dispersion compensator (cylindrical lens and membrane not to scale). A circulator, not shown, is connected to the I/O waveguide. (b) Schematic of how variable curvature is achieved by buckling the reflective membrane (top: unactuated, bottom: buckled).

### 3. Results

We cut a strip of 2-mil-thick aluminum-coated Mylar, 2.5-mm wide, and glued its ends to two piezo-electric actuators each with 15- $\mu\text{m}$  achievable displacement. We placed springs in between to tension the arrangement. We then took the silica waveguide chip with the WGR, cut a slot in it, inserted the waveplate, glued on the input/output fiber, attached it to a circulator, and glued on the plano-cylindrical lens. We then brought up the deformable mirror assembly and aligned it using a 6-axis stage. The non-zero diffraction orders from the WGR were extinguished by placing an aperture at the mirror plane. Both piezo-electric actuators were wired in parallel, so only one voltage knob was required to adjust the dispersion.

The TDC demonstrated more than  $\pm 500$  ps/nm tuning range, as designed (Fig. 2a). The group delay ripple (GDR) was less than  $\pm 6$  ps over 70-GHz of bandwidth, for support of 40-Gb/s transmission rates (Fig 2b). At the extreme tuning positions the transmissivity passband exhibited narrowing (Fig. 2c) because the mirror deflects the spectral extremes away from the center of the star coupler. The insertion loss, including the circulator, was  $\sim 10 \pm 2$  dB (dispersion-setting dependent). The polarization-dependent loss across a 70-GHz bandwidth ranged from 0.5 dB at 0 ps/nm to 3.5 dB at the tuning extremes. Likewise, worst-case differential group delay (DGD) varied from  $< 1$  ps at 0 ps/nm to  $< 7$  ps at the tuning extremes. The Mylar film contributed to some of the polarization performance degradations; a fixed parabolic gold-on-glass mirror exhibited significantly less PDL and DGD.

The compensation capability of the TDC was tested using a 42.7-Gb/s carrier-suppressed return-to-zero (CSRZ)  $2^{31}-1$  pseudo-random bit sequence at 1550 nm, with different spools of fibers placed between the transmitter and receiver to generate the dispersion. CSRZ is a stringent test of a TDC because of its wide bandwidth. At the receiver, a wavelength demultiplexer preceded the TDC, followed by an optical preamplifier and a p-i-n photodetector into a 40-Gb/s electrical demultiplexer. No polarization control was allowed. At the 0-ps/nm setting, the TDC showed zero penalty in bit-error rate (BER) vs. optical signal-to-noise ratio (OSNR) over the back-to-back case (Fig. 2d). Penalty at the dispersion extremes of  $\pm 500$  ps/nm was  $\sim 1$  dB OSNR at  $10^{-3}$  BER and  $\sim 3$  dB OSNR at

$10^{-9}$  BER. We attribute the greater penalty with negative dispersion (as the Mylar film flattens) to the passband narrowing, as the GDR is well behaved throughout the tuning range.

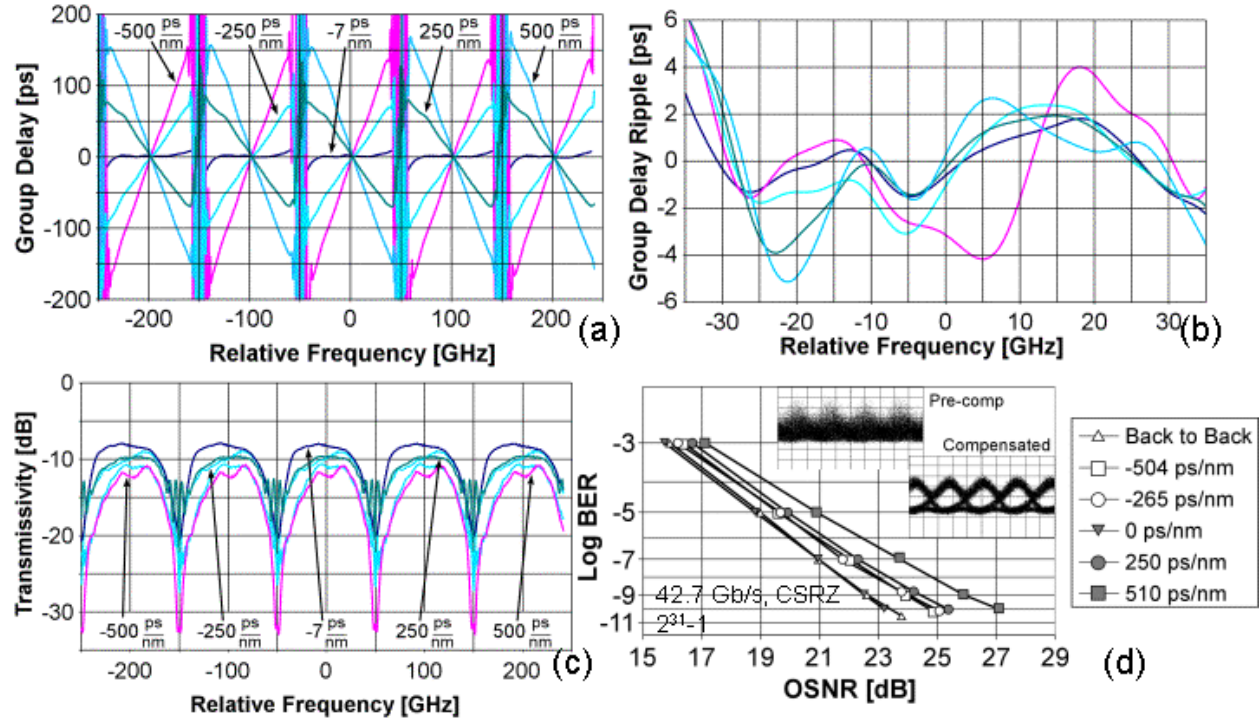


Fig. 2. TDC measurements of at five different dispersion settings of (a) group delay, (b) group-delay ripple, (c) transmissivity, and (d) BER vs. OSNR (0.1-nm bandwidth) and eye diagrams.

The time responses to increase and decrease the dispersion are 10 ms and 1 ms, respectively. The time to decrease the dispersion (flatten the mirror) is longer most likely because of the restoring force of the springs.

In summary, we demonstrated a novel TDC that combines waveguides and mechanical optics to achieve a large tuning range with single-knob tuning, a small size, fast adjustment, low power consumption, and a free-spectral range that matches the usual channel spacing for 40-Gb/s systems.

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