An optical true time delay line (OTTDL) is a fundamental building block for signal processing applications in microwave photonics (MWP) and optical communications. Here, we experimentally demonstrate an index-variable OTTDL based on an array of forty subwavelength grating (SWG) waveguides on silicon-on-insulator (SOI). Each SWG waveguide in the array is 34 mm long and arranged in a serpentine manner; the average incremental delay between waveguides is about 4.7 ps and the total delay between the first and last waveguides is approximately 181.9 ps. The waveguide array occupies a chip area of ~ 6.5 mm × 8.7 mm = 56.55 mm². The proposed OTTDLs bring potential advantages in terms of compactness as well as operation versatility to a variety of microwave signal processing applications.

http://dx.doi.org/10.1364/OL.99.099999
properly designing the physical dimensions and material doping concentration of each core in a way that the cores feature the required differential chromatic dispersion profile for tunable operation [14]. Inspired by this approach, we proposed and demonstrated for the first time how a group of equal-length SWG waveguides can be used to implement an integrated version of a heterogeneous multicore fiber as a sampled index-variable OTTDL [15]. In particular, we showed that a group of four SWG waveguides of the same length can provide different propagation velocities by tailoring the effective index of each SWG waveguide through control of their corresponding duty cycles and verified its OTTDL nature.

Here, we significantly extend our proof-of-concept in [15] by making the following changes/advances: (1) we increase the length of the waveguides by more than a factor of 4 to 34 mm, (2) we use a serpentine arrangement, (3) we vary the duty cycle in 1% increments (as opposed to 10% increments), and (4) we realized forty SWG waveguides to provide 40 unique delay lines. These advances are significant because of the following: previously, we achieved a maximum differential delay (between the first and last waveguides) of only 27.5 ps with an average incremental delay (between consecutive waveguides) of 9.2 ps; on the other hand, we now achieve a maximum differential delay of 181.9 ps with an average incremental delay of only 4.7 ps. In other words, increasing the length of the waveguides allows for a greater maximum differential delay while reducing the duty cycles allows for a smaller incremental delay (it should be noted that smaller incremental delays are possible with shorter length waveguides). Moreover, the use of a serpentine arrangement for the longer waveguides has allowed us to maintain a similar chip length (i.e., 8.7 mm compared to 8.06 mm). Finally, with our new realization, we have been able to ascertain that a variation in duty cycle as low as 1% is possible and within fabrication capabilities. We also note that increasing the number of waveguides to 40 provides greater tunability/reconfigurability for systems applications, e.g., in microwave photonic filtering or optical beamforming, as well as flexibility, e.g., it is possible to use the same waveguide array to implement in parallel different signal processing functions, for instance, by devoting $n$ samples (waveguides) to one functionality and the remaining $40-n$ samples to a second functionality.

An index-variable OTTDL generally involves waveguides of the same length but the propagation velocities are different. The group index of the SWG waveguides can be engineered to control the incremental time delay by choosing the duty cycles of each SWG.

---

**Fig. 1.** Design of the SWG-waveguide-based OTTDL. (a) Schematic of the fabricated array of forty SWG waveguides in SOI (the different colors represent different duty cycles of the SWG waveguides). (b) Details of the waveguide bends. (c) The waveguide cross-section view.

---

**Fig. 2.** (a) Experimental setup to measure the power spectral response of the fabricated index-variable OTTDL. (b) Experimental time-of-flight measurement setup. ASE: amplified spontaneous emission source; OSA: optical spectrum analyzer; LD: laser diode; EOM: electro-optic intensity modulator; EDFA: erbium-doped optical fiber amplifier; DCA: digital communication analyzer; RF: RF generator.
The group index of an SWG waveguide can be expressed as [15]:

\[
n_g = \frac{n_1 n_2 D + n_2 n_{g2}(1 - D)}{\sqrt{D n_1^2 + (1 - D) n_2^2}},
\]

where \( n_1 \) and \( n_2 \) are the effective indices of the silicon and silica waveguides, respectively, \( n_{g1} \) and \( n_{g2} \) are the group index of the silicon and silica waveguides and \( D \) is the duty cycle of the SWG defined earlier.

To investigate the performance of the integrated index-variable OTTDL, we fabricated an array of forty SWG waveguides in SOI, see Fig. 1(a). The SWG waveguides are formed by alternating periodically segments of silicon and silica with a period of \( \Lambda = 250 \) nm. Each waveguide in the array is 34-mm long and the duty cycles are varied in 1% increments from 30% to 69%. The waveguides are arranged in a serpentine configuration to reduce size; each bend includes two SWG tapers to transition between the SWG waveguide and solid core waveguide used as the waveguide size; each bend includes two SWG tapers to transition between the waveguides. The SWG waveguides have a cross-section of 220 nm \( \times \) 500 nm; they are covered by an index-matched cladding layer of thickness 22 \( \mu \)m. Each SWG waveguide has an input and output taper for coupling to a nanowire waveguide of the same cross-section, as illustrated in Fig. 1(c). The SWG tapers are used for mode conversion between the SWG waveguide and the solid core waveguide [15]. The duty cycle of the taper is the same as the duty cycle of the SWG waveguide, and the thickness of waveguides is 220 nm. The length of a taper is 50 \( \mu \)m.

The chip is fabricated using electron beam lithography with a single etch at Applied Nanotools. The SWG waveguides have a cross-section of 220 nm \( \times \) 500 nm; they are covered by an index-matched cladding layer of thickness 22 \( \mu \)m. Each SWG waveguide has an input and output taper for coupling to a nanowire waveguide of the same cross-section, as illustrated in Fig. 1(c). The SWG tapers are used for mode conversion between the SWG waveguide and the solid core waveguide [15]. The duty cycle of the taper is the same as the duty cycle of the SWG waveguide, and the thickness of waveguides is 220 nm. The length of a taper is 50 \( \mu \)m.

We use an EDFA as an amplified spontaneous emission (ASE) source and an optical spectrum analyzer (OSA) to obtain the spectral response of each SWG waveguide, as shown in Fig. 2(a). The experimental setup to measure the propagation time for the time-of-flight measurement is illustrated in Fig. 2(b). A tunable laser generates a continuous wave at 1550 nm with an output power of \( \sim 6 \) dBm. The laser is modulated employing an electro-optic modulator (EOM) driven by an RF signal of 10 GHz. After propagating through each SWG waveguide, the signals are amplified by a low-noise EDFA and then detected and observed using a digital communication analyzer (DCA). The incremental delays are extracted from the measured waveforms using the measured trace from the first waveguide as a reference.

Fig. 3(a) shows the spectra at the output of the waveguides as well as that of the input broadband source and confirms the broadband nature of the SWG waveguides (note that we did not optimize coupling for each measurement). To measure the total fiber-to-fiber loss, we replaced the ASE source by a laser set to 1550 nm and optimized the coupling for each SWG waveguide; the results are summarized in Fig. 3(b). The average fiber-to-fiber loss is approximately 33 dB, of which \( \sim 20 - 22 \) dB is due to the vertical grating coupler (VGC) losses (measured separately using VGC-to-VGC test structures). Other losses include losses from the taper between nanowire and SWG waveguides, waveguide bend losses, and the propagation loss in the SWG waveguide. The tapers losses between the nanowire and SWG waveguides vary with duty cycle and from simulations, we observe a loss of 0.07 - 0.08 dB/taper. We then estimate the total losses from the tapers to be 0.56 - 0.64 dB (there are 8 tapers in each waveguide). The loss of a nanowire waveguide bend with a bend radius > 10 \( \mu \)m is < 0.5 dB at 1550 nm [17]. The total losses from waveguide bends is then about 1.5 dB (there are 3 bends in each waveguide). Therefore, the SWG waveguide propagation losses are about 9 - 11 dB over their 34 mm length, corresponding to a propagation loss of 2.6 - 3.2 dB/cm, which agrees with values reported in the literature [18] as well as for conventional nanowire waveguides in SOI.

The total fiber-to-fiber loss can be reduced through the following. First, as the duty cycles of the SWG waveguides are varied, the corresponding tapers can be optimized separately to reduce the mode mismatch loss. Second, and most importantly, we can reduce the VGC coupling loss significantly: for instance, Wen et al. demonstrated a VGC design with a loss of 1.7 dB [19].

Through time-of-flight measurement, we get the results shown in Figs. 3(c) and 4. Fig. 3(c) shows the measured time delays in the waveguides, which increases linearly as a function of duty cycle (apart from a few waveguides which may have been impacted by fabrication and processing errors and variations given the small changes in duty cycle; we believe that these also contribute to the ‘spikes’ in the fiber-to-fiber losses shown in Fig. 3(b)). The average incremental time delay between consecutive SWG waveguides is about 4.7 ps. The total time delay between the first and last SWG waveguides is approximately 181.9 ps. Fig. 4 shows the measured time delays of the OTTDLs at different wavelengths. These results also verify that our index-variable OTTDL has a wide optical...
bandwidth from 1540 nm to 1565 nm (such a wide operating bandwidth can be useful in MWP applications requiring multiple optical carriers).

There are some advantages of our index-variable OTTDL comparing with other OTTDL approaches. For example, in the length-variable OTTDL in SOI in [20], obtaining a total delay of 180 ps requires a length difference of ~ 14 mm between the shortest and longest waveguides which will increase the size of the device. On the other hand, our index-variable OTTDL ensures that all SWG waveguides are of the same length. Another popular approach to implement ODLs is to use linearly chirped waveguide Bragg gratings [21]; however, as wavelength-variable ODLs, they cannot provide time delays for signals at the same wavelength. Moreover, obtaining a longer delay range requires longer waveguides. Finally, the use of coupled ring resonators requires careful control over the coupling coefficients [22]. Note that since the propagation losses in our SWG waveguides is comparable to those of nanowire waveguides in SOI, the loss per unit time delay is expected to be similar. Other material platforms, e.g., silicon nitride, offer lower propagation losses and potentially, lower loss per unit time delay.

We also note that continuous tuning of the delay should be possible by changing the wavelength of the optical carrier as observed using heterogeneous multicore fibers [14]. In particular, by operating closer to the SWG waveguide band edge, we may be able to take advantage of the increased dispersion in order to have different incremental values of dispersion and hence group delays as the wavelength of the optical carrier is tuned. In addition, increasing the number of SWG waveguides can provide more options for microwave photonics applications. It should be possible to increase the number of the SWG waveguides by reducing the increment in duty cycle. For example, the increment in duty cycle can be reduced or the range of duty cycles can be increased, thereby allowing for an increase in the number of SWG waveguides in the array. However, these will be limited by either the resolution of ebeam lithography or higher taper and propagation losses [16, 23].

In summary, we have proposed and designed experimentally an OTTDL based on an array of forty SWG waveguides in SOI, where each waveguide is 34-mm long. By controlling the duty cycles which are varied in 1% increments from 30% to 69%, an average incremental delay of about 4.7 ps and a total delay between the first and last waveguides of approximately 181.9 ps can be obtained. Our work has allowed us to achieve a higher performance OTTDL while ensuring a compact size, enhance applications with one single chip, and allow us to establish what can be realized with existing fabrication capabilities. We believe that our SWG-waveguide-based OTTDL offers a versatile and compact solution to enable a wide range of integrated MWP signal processing functions for enhanced radar, communications, sensing, and instrumentation applications. Beyond MWP, this approach can be extended to perform additional optical signal processing applications that require different values of the group delay.

**Funding.** Natural Sciences and Engineering Research Council of Canada; China Scholarship Council; European Research Council under Consolidator Grant Project (724663).

---

**Fig. 4.** Measured time delays of the 40 SWG waveguides at different wavelengths.

---

**References**

1. J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Lloret, and S. Sales, J. Light. Technol. 31, 571 (2012).
2. J. Capmany, and D. Novak, Nat. Photonics 1, 319 (2007).
3. C. G. H. Roeloffzen, L. Zheng, C. Taddei, A. Leinse, R. G. Heideman, P. W. L. Van Dijk, R. M. Oldenbeuving, D. A. I. Marpaung, M. Burla, and K. J. Boller, Opt. Express 21, 22937-22961 (2013).
4. R. A. Minasian, E. H. W. Chan, and X. Yi, Opt. Express 21, 22918 (2013).
5. J.-D. Shin, B.-S. Lee, and B.-G. Kim, IEEE Photon. Technol. Lett. 16, 1364-1366 (2004).
6. X. Ye, F. Zhang, and S. Pan, Opt. Exp. 23, 10002 (2015).
7. I. Giuntoni, D. Stolarek, D. I. Kroushkov, I. Bruns, L. Zimmermann, B. Tillack, and K. Petermann, Opt. Exp. 20, 11241 (2012).
8. A. Choudhary, Y. Liu, B. Morrison, K. Vu, D. Y. Choi, P. Ma, S. Madden, D. Marpaung, and B. J. Eggleton, Sci. Rep. 7, 5932 (2017).
9. L. R. Chen, J. Light. Technol. 35, 824 (2016).
10. J. Xie, L. Zhou, Z. Zou, J. Wang, and J. Chen, Opt. Exp. 22, 817 (2014).
11. P. Cheben, R. Halir, J. H. Schmid, H. A. Atwater, and D. R. Smith, Nature 560, 565 (2018).
12. P. J. Bock, P. Cheben, J. H. Schmid, J. Lapointe, A. Delâge, S. Janz, G. C. Aers, D.-X. Xu, A. Densmore, and T. J. Hall, Opt. Exp. 18, 20251 (2010).
13. I. Gasulla, and J. Capmany, IEEE Photon. J. 4, 877 (2012).
14. S. García, and I. Gasulla, Opt. Exp. 24, 20641 (2016).
15. J. Wang, R. Ashrafi, R. Adams, I. Glesk, I. Gasulla, J. Capmany, and L. R. Chen, Sci. Rep. 6, 30235 (2016).
16. V. Donzella, A. Sherwali, J. Flueckiger, S. T. Fard, S. M. Grist, and L. Chrostowski, Opt. Exp. 22, 21037 (2014).
17. L. Chrostowski, and M. Hochberg, Silicon Photonics Design: From Devices to Systems (2015).
18. L. R. Chen, J. Wang, B. Naghdi, and I. Glesk, "Subwavelength Grating Waveguide Devices for Telecommunications Applications," IEEE J. Sel. Top. Quantum Electron. 25, 82001 (2018).
19. W. Zhou, Z. Cheng, X. Chen, K. Xu, X. Sun, and H. K. Tsang, IEEE J. Sel. Top. Quantum Electron. 25, 2900113 (2019).
20. J. Xie, L. Zhou, Z. Li, J. Wang, and J. Chen, Opt. Exp. 22, 22707 (2014).
21. W. Zhang and J. Yao, J. Light. Technol. 34, 4664 (2016).
22. M. S. Rasras, C. K. Madsen, and M. A. Cappuzzo, IEEE Photon. Technol. Lett. 17, 834 (2005).
23. L. Chrostowski, X. Wang, J. Flueckiger, Y. Wu, Y. Wang, and S. T. Fard, in Optical Fiber Communication Conference(Optical Society of America 2014), p. 37.
1. J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Lloret, and S. Sales, "Microwave photonic signal processing," J. Light. Technol. 31, 571-586 (2012).
2. J. Capmany, and D. Novak, "Microwave photonics combines two worlds," Nat. Photonics 1, 319-330 (2007).
3. C. G. H. Roeloffzen, L. Zhuang, C. Taddei, A. Leinse, R. G. Heideman, P. W. L. Van Dijk, R. M. Oldenbeuving, D. A. I. Marpaung, M. Burla, and K. J. Boller, "Silicon nitride microwave photonic circuits," Opt. Express 21, 22937-22961 (2013).
4. R. A. Minasian, E. H. W. Chan, and X. Yi, "Microwave photonic signal processing," Opt. Express 21, 22918-22936 (2013).
5. J.-D. Shin, B.-S. Lee, and B.-G. Kim, "Optical true time-delay feeder for X-band phased array antennas composed of 2/spl times/2 optical MEMS switches and fiber delay lines," IEEE Photon. Technol. Lett. 16, 1364-1366 (2004).
6. X. Ye, F. Zhang, and S. Pan, "Optical true time delay unit for multi-beamforming," Opt. Express 23, 10002-10008 (2015).
7. I. Giuntoni, D. Stolarek, D. I. Kroushkov, J. Bruns, L. Zimmermann, B. Tillack, and K. Petermann, "Continuously tunable delay line based on SOI tapered Bragg gratings," Opt. Express 20, 11241-11246 (2012).
8. A. Choudhary, Y. Liu, B. Morrison, K. Vu, D. Y. Choi, P. Ma, S. Madden, D. Marpaung, and B. J. Eggleton, "High-resolution, on-chip RF photonic signal processor using Brillouin gain shaping and RF interference," Sci. Rep. 7, 5932 (2017).
9. L. R. Chen, "Silicon photonics for microwave photonics applications," J. Light. Technol. 35, 824-835 (2016).
10. J. Xie, L. Zhou, Z. Zou, J. Wang, and J. Chen, "Continuously tunable reflective-type optical delay lines using microring resonators," Opt. Express 22, 817-823 (2014).
11. P. Cheben, R. Halir, J. H. Schmid, H. A. Atwater, and D. R. Smith, "Subwavelength integrated photonics," Nature 560, 565-572 (2018).
12. P. J. Bock, P. Cheben, J. H. Schmid, J. Lapointe, A. Delâge, S. Janz, G. C. Aers, D.-X. Xu, A. Densmore, and T. J. Hall, "Subwavelength grating periodic structures in silicon-on-insulator: a new type of microphotonic waveguide," Opt. Express 18, 20251-20262 (2010).
13. I. Gasulla, and J. Capmany, "Microwave photonics applications of multicore fibers," IEEE Photon. J. 4, 877-888 (2012).
14. S. Garcia, and I. Gasulla, "Dispersion-engineered multicore fibers for distributed radiofrequency signal processing," Opt. Express 24, 20641-20654 (2016).
15. J. Wang, R. Ashrafi, R. Adams, I. Glesk, I. Gasulla, J. Capmany, and L. R. Chen, "Subwavelength grating enabled on-chip ultra-compact optical true time delay line," Sci. Rep. 6, 30235 (2016).
16. V. Donzella, A. Sherwali, J. Flueckiger, S. T. Fard, S. M. Grist, and L. Chrostowski, "Sub-wavelength grating components for integrated optics applications on SOI chips," Opt. Express 22, 21037-21050 (2014).
17. L. Chrostowski, and M. Hochberg, Silicon Photonics Design: From Devices to Systems (2015).
18. L. R. Chen, J. Wang, B. Naghdi, and I. Glesk, "Subwavelength grating waveguide devices for telecommunications applications," IEEE J. Sel. Top. Quantum Electron., 25, 82001 (2018).
19. W. Zhou, Z. Cheng, X. Chen, K. Xu, X. Sun, and H. K. Tsang, "Subwavelength engineering in silicon photonic devices," IEEE J. Sel. Top. Quantum Electron. 25, 2900113 (2019).
20. J. Xie, L. Zhou, Z. Li, J. Wang, and J. Chen, "Seven-bit reconfigurable optical true time delay line based on silicon integration," Opt. Express 22, 22707-22715 (2014).
21. W. Zhang, and J. Ya, "Silicon-based on-chip electrically-tunable spectral shaper for continuously tunable linearly chirped microwave waveform generation," J. Light. Technol. 34, 4664-4672 (2016).
22. M. S. Rasras, C. K. Madsen, and M. A. Cappuzzo, "Integrated resonance-enhanced variable optical delay lines," IEEE Photon. Technol. Lett. 17, 834-836 (2005).
23. L. Chrostowski, X. Wang, J. Flueckiger, Y. Wu, Y. Wang, and S. T. Fard, "Impact of fabrication non-uniformity on chip-scale silicon photonics integrated circuits," in Optical Fiber Communication Conference (Optical Society of America 2014), p. Th2A.37.