Multi-Cavity Optoelectronic Oscillators Based on an Integrated Array of Subwavelength Grating Waveguides

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Abstract—We demonstrate experimentally an index-variable optical true time delay (OTTDL) based on an array of forty subwavelength grating (SWG) waveguides on silicon-on-insulator (SOI). Using the measured data and numerical simulations, we determine the oscillation spectra, phase noise, and frequency tuning of the multi-cavity OEOs. Moreover, the proposed SWG based multi-cavity OEOs do not require highly selective RF filters, which enables high performance of SWG based multi-cavity OEO.

Keywords—Silicon photonics, microwave photonics, optoelectronic oscillators, optical true time delay lines

I. INTRODUCTION

Photonic signal processing provides an opportunity to overcome the limitation of electronic bottleneck effect due to its advantages such as broad operation bandwidth, immunity to electromagnetic interference [1]. Optical true time delays (OTTDLs) are a basic building block in microwave photonics (MWP) systems and optical communications. For example, OTTDLs are used to develop MWP filters [2], optical beamforming in phased array antennas [3], and OEOs [4]. Characteristics of OTTDLs include, amongst others, operating bandwidth, total time delay, and size of the delay increments for discrete delays [5, 6]. For integrated OTTDLs, compactness and insertion loss are also important characteristics. Recently, there has been significant interest in developing subwavelength grating (SWG) waveguide structures as OTTDLs for high performance photonic integrated circuits on silicon-on-insulator (SOI) [7]. Characteristics of SWG waveguides, such as low loss and the flexibility of effective refractive index, can result in enhanced performance compared to conventional SOI nanowire-based devices [8].

In this paper, we significantly extend the proof-of-concept demonstrated in [9] and demonstrate an array of forty SWG waveguides to implement the application of multi-cavity OEOs. We fabricate an index-variable OTTDL based on an array of forty SWG waveguides in a serpentine manner with a simple geometry in SOI. The OTTDL involves waveguides of the same length but different propagation velocities, and they are achieved by tailoring the effective index of SWG waveguides by controlling their duty cycles. Besides, we simulate the unbalanced dual-cavity OEO with a discretely tunable frequency from 6.54 GHz to 38.63 GHz and a multi-cavity OEO with a discretely tunable frequency from ~ 20 GHz to ~ 22.2 GHz.

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II. DESIGN CHARACTERIZATION OF THE SWG WAVEGUIDE-BASED OTTDLS

We design and fabricate an array of forty separate 34 mm long SWG waveguides with different duty cycles. The duty cycles of SWG waveguides are varied in 1% increments from 30% to 69%. The SWG waveguides are realized by alternating periodically segments of silicon and silica, with a period of $\lambda = 250 \text{ nm}$ along the propagation direction. The group index of the SWG waveguides can be engineered to control the incremental time delay by choosing the duty cycle $\eta = \frac{a}{\lambda}$, where $a$ is the length of the silicon segment in each period. Fig. 1(a) shows a schematic of the array with a serpentine configuration in a compact chip area. Each SWG waveguide is 34 mm long and separated by $\sim 31.5 \mu\text{m}$ in order not to have any crosstalk between the waveguides. The structure of the bends includes two SWG tapers, two solid waveguide bends, and one solid waveguide, as shown in Fig. 1(b). The SWG tapers are used for mode conversion between the SWG waveguide and the solid waveguide [9]. 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. Each SWG waveguide has an input and output taper for coupling to a nanowire waveguide of the same cross-section. The length of a taper is 50 $\mu\text{m}$, and the width is 500 nm (as well as the width of the SWG waveguides). The chip is fabricated using electron beam lithography with a single etch at the Applied Nanotools (ANT) Inc.

The setup for time-of-flight measurements to obtain the differential time delays between the RF signals provided by the different OTTDLs at an optical carrier wavelength of 1550 nm is shown in Fig. 1(c). Fig. 2 (a) shows the results of the measured differential time delays. The index-variable OTTDL has an average incremental time delay of $\sim 4.7 \text{ ps}$ between the taps. Then, we use an amplified spontaneous emission (ASE) source and an optical spectrum analyzer (OSA) to observe the optical spectral responses of forty SWG waveguides. Fig. 2(b) shows the output spectra from the OSA. The total fiber-to-fiber loss depends on coupling loss associated with the vertical grating couplers (VGCs), propagation loss in the SWG waveguide and the mode mismatch loss between the SWG waveguide and nanowire pronounced. The optimized average of each total fiber-to-fiber loss of our OTTDL is $\sim 33 \text{ dB}$. The loss of each waveguide can be reduced by using higher efficiency VGCs, which can improve losses up to $10 \sim 15 \text{ dB}$.

III. APPLICATION OF MULTI-CAVITY OEOS USING FABRICATED SWG WAVEGUIDES

Fig. 3 shows the layout of multi-cavity OEOS based on our SWG waveguides. The basic principle of the multi-cavity OEOS can be found in [10, 11].

A. Spectra of multi-cavity OEOS

The output RF power of a multi-cavity OEO can be described by [11]:

$$P(\omega) = \left( \frac{G_a^2}{2R} \right) \frac{\left| V_{in}(\omega) \right|^2}{\left[ 1 - \sum_{k=1}^{N} |g_k| e^{i(\omega_0 + \phi_k)} \right]^2}$$

where $g_a V_{in}(\omega)$ is the starting voltage of oscillation and $G_a$ is the RF amplifier gain, $R$ is the load impedance, $g_k$ is the complex gain of $k^{th}$ cavity and

$$\Phi_k(\omega) = \omega \tau_k + \phi_k,$$

where $\Phi_k$ is the phase factor of complex gain $g_k$.

For the oscillations to start collectively in all cavities and start from noise, we consider a simple case that the gain coefficients have equal value in all cavities, i.e., $|g_k| = 1/N$. $N$ is the number of cavities in the multi-cavity OEO.

B. Phase noise

The phase noise model of the multi-cavity OEO is also
investigated. The power spectral density of the mode oscillating at $\omega_0$ can be expressed as \([11]\):

$$S_{RF}(f') = \frac{G_a^2 \rho_n^2}{P_{osc}} \left[1 - \sum_{k=1}^{N} |g_k|^2 e^{i(2\pi f' r_k)}\right]^2$$

where $\omega_0$ is the oscillation angular frequency, $f' = \frac{\omega - \omega_0}{2\pi}$ is the offset frequency from the RF carrier, $P_{osc}$ represents the RF oscillation power, $\rho_n$ is all the technical noise sources of the OEO \([12]\).

**C. Unbalanced dual-cavity OEOs**

Fig. 3(a) illustrates the scheme of an unbalanced dual-cavity OEO. For this configuration, the oscillation frequency must satisfy \([11]\):

$$f_0 = \frac{k}{\tau_1} = \frac{n}{\tau_2}$$

where $k$ and $n$ are integers, and $\tau_1$ and $\tau_2$ are the cavity time delays of two cavities, respectively.

Equation (4) is used to determine the values of $\tau_1$ and $\tau_2$. We select two SWG waveguides whose delays satisfy (4): for example, we choose the fifth SWG waveguide and thirty-eighth waveguide which have delays of 305.8 ps and 458.9 ps, respectively, leading to $k=2, n=3$ and $f_0 \sim 6.54$ GHz, the oscillation spectrum is shown in Fig. 4(a). By the same token, other examples of unbalanced dual-cavity OEOs are simulated in Figs. 4(b) and (c). A discretely tunable dual-cavity OEO whose frequency from 6.54 GHz to 38.63 GHz is then realized.

Fig. 5 shows the simulated results of the phase noise spectra for the unbalanced dual-cavity OEO using our fabricated SWG waveguides. The standard noise is $\rho_n = -180$ dBc/Hz, the gain of the RF amplifier is $G_a=10 \text{ dBm}$ and the oscillation power is $P_{osc} = 16 \text{ dBm}$. The results show the phase noise of all unbalanced configurations behave similarly because the phase noise is determined by the longer cavity. The change in the longer cavity length of our configuration has an almost negligible effect in the resonance quality factor. However, we suffer more from the phase noise because of our ps magnitude delays. The results illustrate the phase noise of the oscillator is almost independent of oscillation frequency, which is one of the advantages of OEOs.

**D. Multi-cavity OEOs**

A multi-cavity OEO can be implemented by using $N$ SWG waveguides as the corresponding $N$ cavities of the OEO, as shown in Fig. 3(b). In this case, equation (2) can be expressed as \([11]\):

$$\Phi_k(\omega) = \omega \tau_1 + (k - 1) \Delta \tau \Delta L + \Phi_T$$

where $k$ is an integer. When $\Phi_k = 0 \forall k$, to start oscillation, the oscillation frequency must satisfy:

$$f_0 = \frac{k}{\tau_1}$$

Fig. 6 shows the simulated oscillation spectra for the multi-cavity OEO. Oscillation frequency of $\sim 20$ GHz for (a) 2 cavities, (b) 3 cavities, and (c) 4 cavities. Oscillation frequency of $\sim 22.2$ GHz for (d) 2 cavities, (e) 3 cavities, and (f) 4 cavities.
simulate the oscillation spectra and phase noise of the measured data of our fabricated index-variable OTTDL, we use the same length but different duty cycles. Then, using the tuned by controlling the duty cycle of the SWGs, which have SOI. The group index and time delay of every OTTDL can be waveguides in a serpentine manner with a simple geometry in index-variable OTTDL based on an array of forty SWG dual-cavity OEO (standard noise suppressed.

We also simulate the spectra of the multi-cavity optoelectronic oscillation over a multicore fiber, "Opt. Express," vol. 25, pp. 23663-23668, 2017.

We simulate a multi-cavity OEO using our SWG-based OTTDL. From our experimentally measured data, we can choose single-cavity delays of 298.6 ps, 346.1 ps, 398.8 ps, and 451.6 ps, respectively. Fig. 6(a), (b), and (c) show the oscillation spectra for the oscillation frequency of ~ 20 GHz and the number of cavities ranges from two to four. To obtain a tunable multi-cavity OEO, we change the delays by selecting different groups of SWG waveguides. For example, we select SWG waveguides with single-cavity delays of 315.8 ps, 360.4 ps, 410.3 ps, and 451.6 ps, the oscillation spectra for the oscillation frequency of ~ 22.2 GHz are shown in Figs. 6(d), (e), and (f). As with unbalanced two-cavity OEO, in all cases, the FSR ranges of multi-cavity OEOs are about GHz magnitude. Thus, a narrow filter is not required since the mode spacing is big. Besides, by increasing the number of cavities, the spurious modes of the multi-cavity OEO can be suppressed.

We also simulate the spectra of the multi-cavity OEO at the frequency of ~ 20 GHz in the same case as unbalanced dual-cavity OEO (standard noise $\rho_b = -180$ dBc/Hz, the gain of the RF amplifier $G_a = 10$ dBm and the oscillation power $P_{osc} = 16$ dBm), as shown in Fig. 7. The results show that the phase noise of each cavity is similar as the delays are slightly different.

IV. SUMMARY

We have designed and demonstrated experimentally an index-variable OTTDL based on an array of forty SWG waveguides in a serpentine manner with a simple geometry in SOI. The group index and time delay of every OTTDL can be tuned by controlling the duty cycle of the SWGs, which have the same length but different duty cycles. Then, using the measured data of our fabricated index-variable OTTDL, we simulate the oscillation spectra and phase noise of the unbalanced dual-cavity OEO and the multi-cavity OEO. The results show the potential of performance with spectral selectivity and tunability. The unbalanced-cavity OEO with a discretely tunable frequency from 6.54 GHz to 38.63 GHz and multi-cavity OEO with a discretely tunable frequency from ~ 20 GHz to ~ 22.2 GHz can be realized. Profit from the delays of our OTTDLs, our proposed OEOs do not need a very narrow filter to obtain single-mode operation because of the big FSR. The proposed OTTDL method provides potential applications in MWP, which will have potential applications in signal processing, radar, communications.

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