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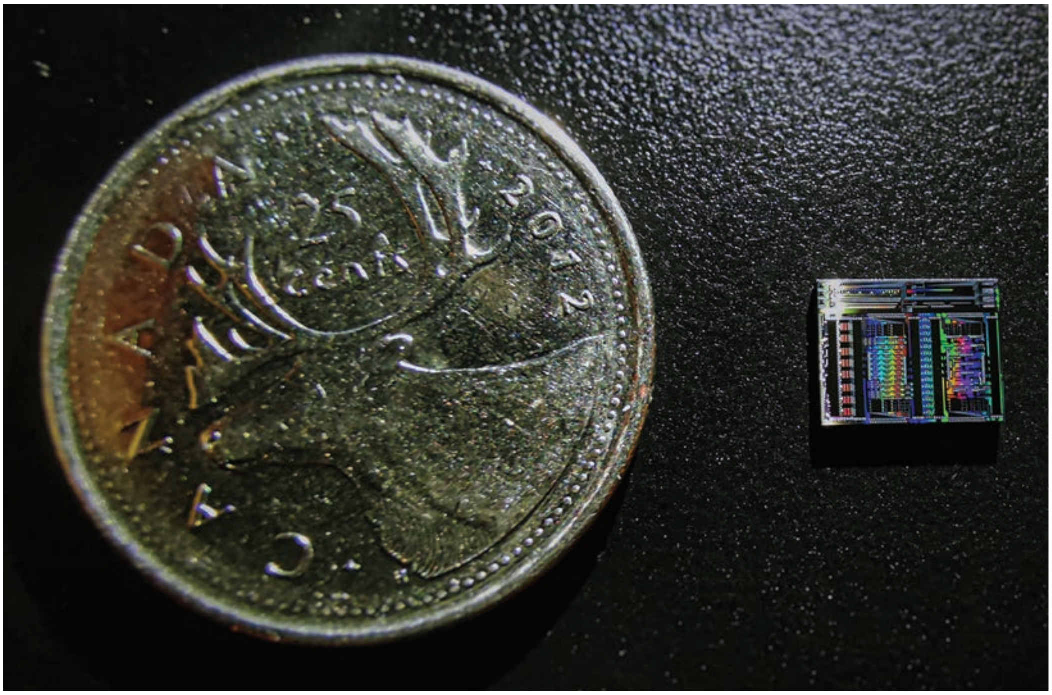

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Research Highlights

On-Chip Programmable Waveguide Bragg Gratings

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In 1913, Bragg's law was formulated. Since then, Bragg gratings, as ubiquitous optical devices, have enjoyed widespread use in various systems. In particular, the successful inscription of a Bragg grating in a fiber core has significantly boosted its engineering applications. To date, most grating devices are specifically designed for a particular use, which limits general-purpose applications since its index modulation profile is fixed after fabrication. To overcome this long-standing limitation, the implementation of a programmable grating, capable of reconfiguring its spectral response by field programming, is a long pursuit.

Introduction

Thanks to the periodic variation of the refractive index in the fiber core or the waveguide, a fiber or waveguide Bragg grating is able to reflect a particular wavelength of light and transmit all others [1]. By specifying its index modulation profile, the spectral response of a Bragg grating could be customized. The simple configuration and unique filtering capability enable a Bragg grating as a versatile optical filter for widespread applications in various scientific and industrial fields [2], [3]. For example, a Bragg grating is inserted into the laser resonator of a solid-state laser to stabilize or tune its emission wavelength. In particular, in 1978, Hill and co-workers discovered fiber Bragg gratings (FBGs), which opened up an unprecedented opportunity to perform optical signal processing and optical fiber sensing [4].

From the beginning of this century, rapid development of semiconductor technologies, especially significant advancement in silicon photonics, has brought Bragg gratings into an on-chip integration era [5]–[7]. Different on-chip waveguide Bragg gratings have been realized on the silicon photonic platform; however, the grating spectral response is predetermined and still cannot be reconfigured after fabrication. Although different mechanisms have been demonstrated to realize spectral tuning, these tuning approaches are mainly limited to shifts of the center wavelength [8], [9]. For many applications, other spectral characteristics, such as spectral shape and phase response, are required to be tunable. For example, with the explosive growth of data traffic, the elastic optical network (EON) architecture is considered a promising solution for next-generation optical networking [10]. Distinct from that in current optical networks, the spectrum grid in an EON is flexible. To address the need for flexible division of the optical spectrum, a reconfigurable optical add-drop multiplexer is an essential component, which can generate elastic optical paths by reconfiguring its filter response [11]. A programmable grating filter is a strong candidate to fulfill this role. To reach the goal, recently, we have reported a programmable waveguide grating in which, by controlling voltages, the grating spectral response can be reconfigured to fit into different applications [12].

Programmable Grating Design

The schematic view of the programmable grating is shown in figure 1. The grating consists of multiple series-connected uniform Bragg grating sections, in which the gratings are produced by creating periodic corrugations on the rib sidewall, and a Fabry-Pérot (FP) cavity section in the middle of the grating. Each uniform Bragg grating section incorporates an

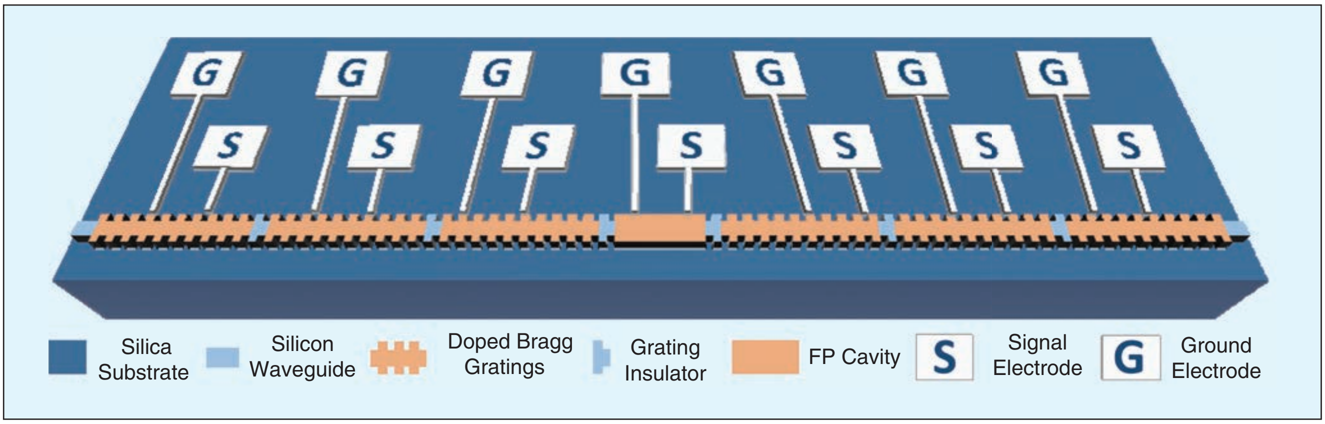

Figure 1. Schematic view of the programmable grating, which consists of multiple series-connected uniform Bragg grating sections and a cavity section in the middle of the grating. Each uniform Bragg grating section incorporates an independent lateral PN junction. A pair of electrodes (Signal and Ground) are connected to each independent PN junction for controlling.

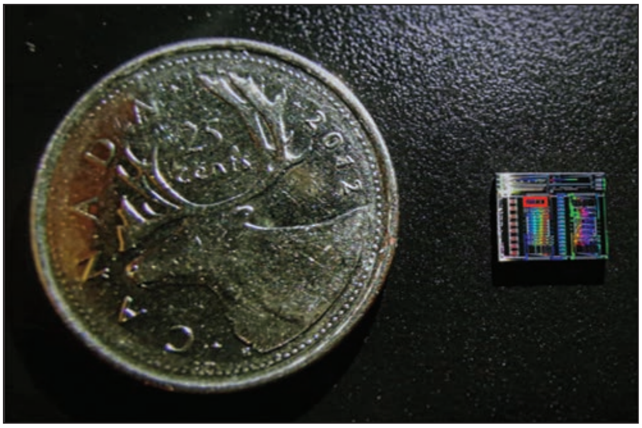

Figure 2. Chip prototype of the programmable grating.

independent lateral PN junction, and between two neighboring sections there is an un-doped grating to function as an insulator. Distributed electrodes are connected to the independent PN junctions. By applying a bias voltage to a PN junction, the refractive index of the grating in that particular section could be tuned locally based on the free-carrier plasma dispersion effect. Thus, the entire index modulation profile of the grating could be electrically reconfigured by field programming all the bias voltages, which enables the grating to have diverse spectral characteristics for diverse applications.

A proof-of-concept demonstration is made in which a programmable grating is designed, fabricated and characterized. Figure 2 shows the chip prototype in which the red line outlines the programmable grating. The device is fabricated at the Institute of Microelectronics (IME, A*STAR, Singapore) in a complementary metal-oxide-semiconductor (CMOS)-compatible process using 248-nm deep ultraviolet lithography. This grating has a symmetrical configuration, which consists of two identical uniform sub-grating sections (left and right) and a FP cavity section in the middle. Each section has an independent PN junction for local tuning. To have a higher tuning efficiency, an asymmetrical lateral PN junction is adopted, which is slightly shifted to the left from the center of the waveguide, to increase the mode overlap with the p-type doping region, since the free-carrier plasma dispersion effect is more sensitive to the change of the free-hole concentration. Three grating couplers are used to couple light between the chip and the input and output fibers, and a compact Y-branch is used to collect the reflected light. To minimize the chip footprint and reduce the bending loss, a strip waveguide is used to guide the optical signal between the grating coupler and the gratings. Since the grating is implemented in a rib waveguide, a double-layer linear taper waveguide is used for the mode transition between the strip and rib waveguides.

Figure 3(a) shows the microscope camera image of the fabricated programmable grating with a length of 1.560 mm and

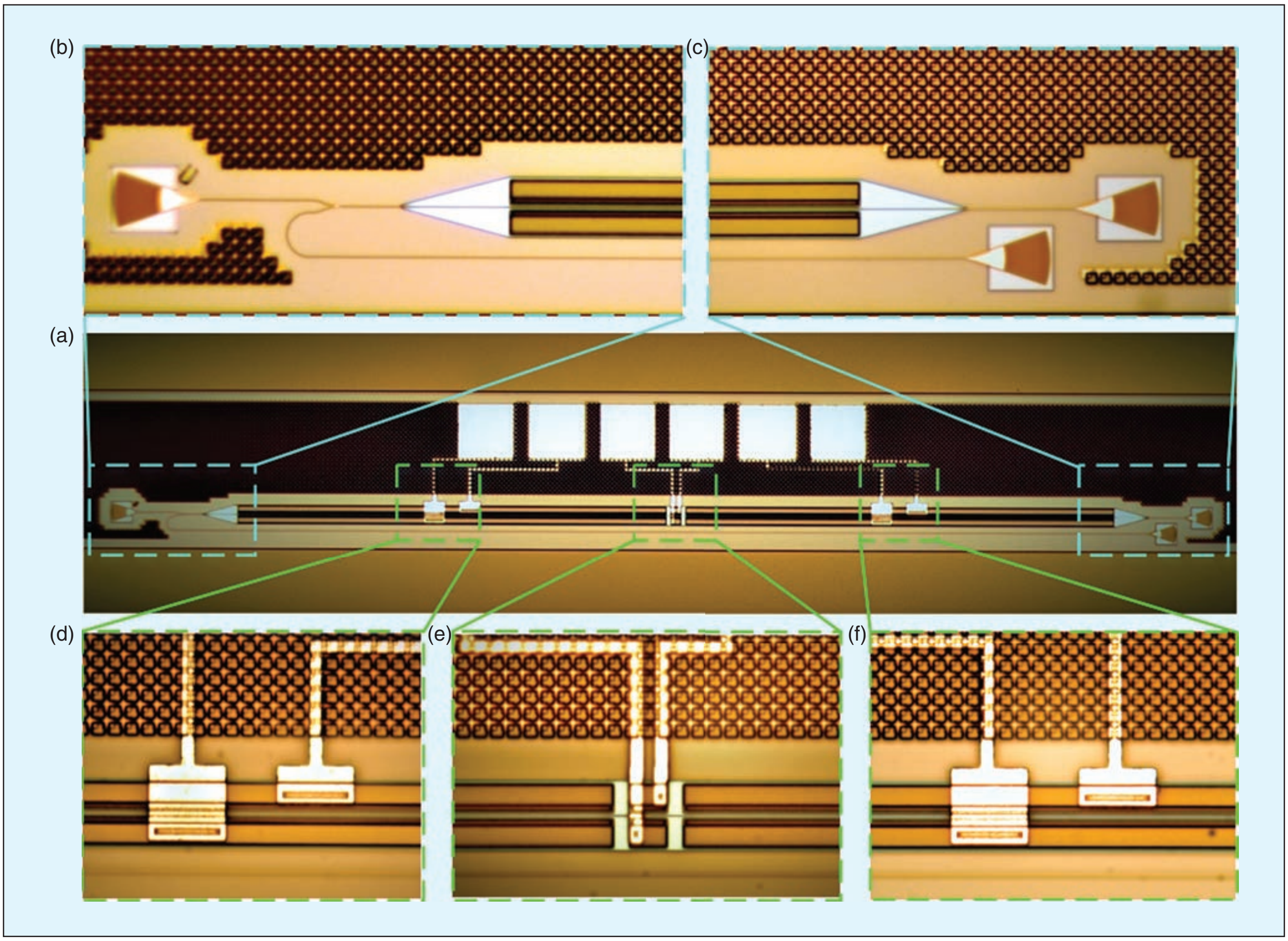

Figure 3. Microscope camera images of the fabricated programmable grating. (a) Entire grating. (b) Input grating coupler and compact Y-branch. (c) Transmission and reflection grating couplers. (d) Left sub-grating section. (e) FP cavity section. (f) Right sub-grating section.

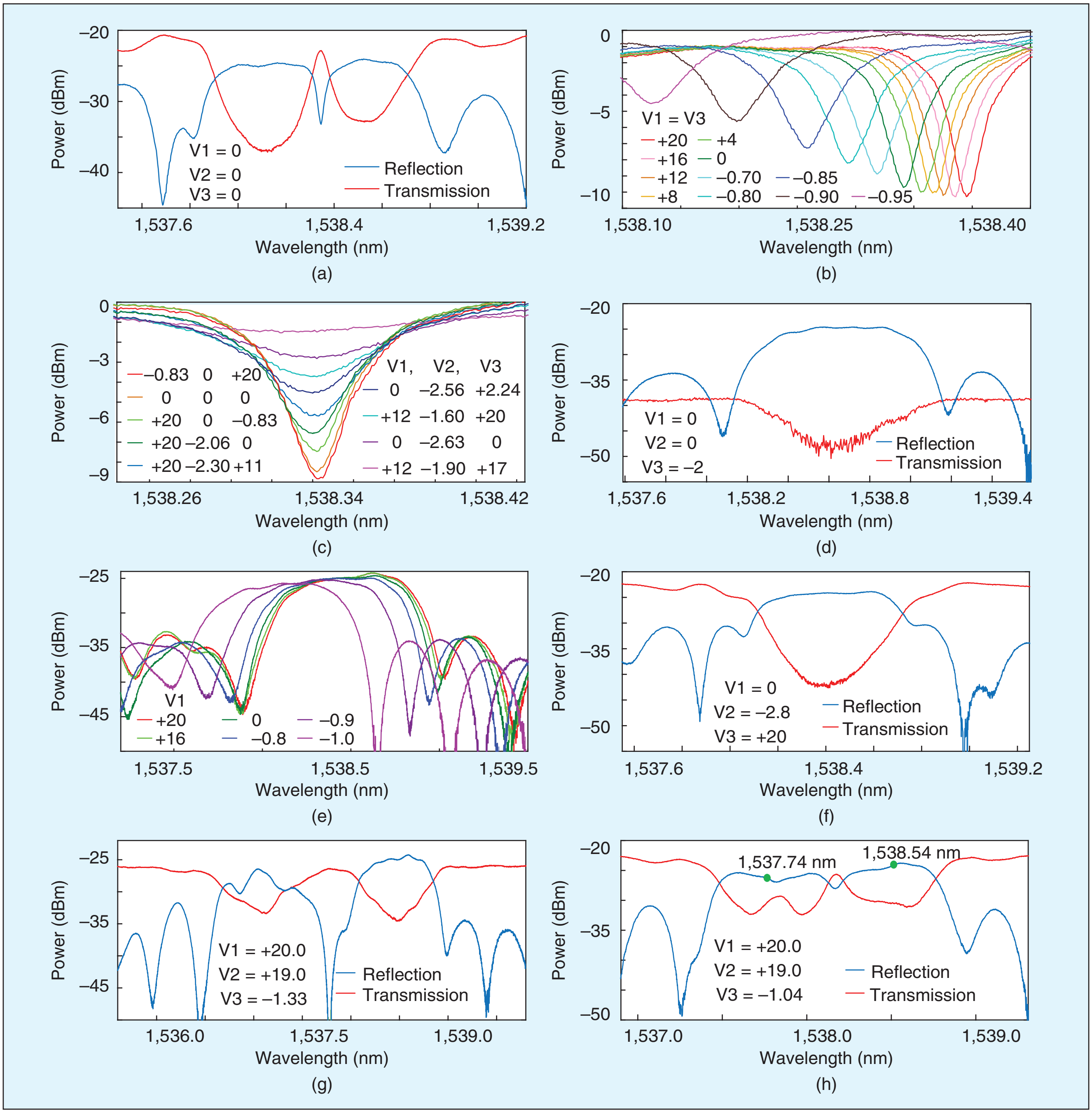

Figure 4. Measured reflection and transmission spectra. (a) Spectra of the fabricated grating in the static state. (b) Notch wavelength shift when the bias voltages applied to the left and right sub-gratings vary synchronously. (c) Extinction ratio tuning while the notch wavelength is kept unchanged. (d) Spectra when the grating is reconfigured to be a uniform grating. (e) Wavelength tuning of the uniform grating. (f) Spectra when the device is reconfigured to be a uniform grating by increasing the cavity loss. (g) Spectra when the device is reconfigured to be two independent uniform sub-gratings. (h) Spectra when the device is reconfigured to be a chirped grating.

a width of 0.196 mm. Figures 3(b-f) give a zoomed-in view of the input grating coupler and the compact Y-branch, the transmission and reflection grating couplers, the left sub-grating section, the FP cavity section, and the right sub-grating section, respectively. Since the local refractive index in each particular section could be tuned by applying a bias voltage to the section PN junction, by field programming three bias voltages, the index modulation profile of the grating can be reconfigured, and thus the grating spectral characteristics can be tailored. Like an amoeba that has the ability to alter its shape, the fabricated programmable grating has the ability to alter its spectral characteristics. In the following section, we experimentally demonstrated a programmable grating, which is electrically reconfigured to be a phase-shifted, a uniform, and a chirped grating by field programming.

Programmable Grating Demonstration

A phase-shifted waveguide Bragg grating can be implemented by introducing a phase shift in the middle of a uniform grating. For the fabricated grating, the phase shift can be introduced by the FP cavity. Figure 4(a) shows the measured reflection and transmission spectra of the fabricated grating in the static state. As can be seen, a resonant window is located within the stopband in the transmission spectra (in red), which is a distinct feature of a phase-shifted Bragg grating.

Figure 4(b) shows a zoomed-in view of the notch wavelength shift in the reflection band when two bias voltages applied to the PN junctions in the left and right sub-grating sections vary synchronously. Thanks to the free-carrier plasma dispersion effect, the free-carrier concentration in the waveguide introduces a change in the refractive index of the waveguide, which leads to the shift of the Bragg wavelength. Figure 4(c) shows the tuning of the extinction ratio while the notch wavelength is maintained unchanged for different bias voltage combinations. It is known that in a conventional phase-shifted Bragg grating, it is not possible to tune the notch extinction ratio while maintaining the notch wavelength unchanged. In the fabricated grating, by field programming the three bias voltages, the notch wavelength shifts induced by the PN junctions could counteract. Thus, the notch wavelength can be preserved, while different bias voltage combinations could lead to a different roundtrip loss, which would result in a different notch extinction ratio.

The fabricated grating can be reconfigured as a uniform grating, which is realized by failing the optical confinement capability of the FP cavity, by applying a large forward bias voltage to the right PN junction. Figure 4(d) gives the measured spectra of the grating when a large forward bias voltage is applied to the right PN junction. The large forward bias voltage enables the injection of massive free-carriers into the waveguide, which would cause a heavy optical absorption loss and thus disable the reflection capability of the right sub-grating. As can be seen, there is one main peak in the reflection or a notch in the transmission spectrum, which is a distinct feature of a uniform grating. In addition, by tuning the bias voltage of the PN junction in the left sub-grating section, the center wavelength of the uniform grating could be tuned as shown in figure 4(e). There is another approach to reconfigure the fabricated grating to be a uniform grating, which is realized by applying a large forward bias voltage to the cavity PN junction. Figure 4(f) gives the measured spectra of the uniform grating when a forward bias voltage is applied to the cavity PN junction. A large forward bias voltage enables the injection of a massive quantity of free-carriers into the cavity to cause a heavy optical absorption loss. Therefore, by programming voltages applied to the PN junctions, the fabricated grating could present some uncommon optical characteristics which are difficult to achieve by using a conventional grating. This is a unique feature of the programmable grating.

Since the PN junctions in the left and right sub-grating sections can be independently controlled, the uniform sub-gratings in the two sections could be tuned independently. Figure 4(g) gives the measured spectra of two uniform sub-gratings when a reverse bias voltage is applied to the left PN junction, and a forward bias voltage is applied to the right PN junction. Thus, the left sub-grating is red shifted and the right sub-grating is blue shifted, which reconfigures the fabricated grating to be two nonidentical uniform sub-gratings. As can be seen, there are two separate main reflection peaks in the reflection spectra. Additionally, the ability to independently tune (and thereby shift the spectral response of) the left and right uniform sub-gratings, enables the device to be reconfigured as a chirped grating. Figure 4(h) presents the measured spectra of the chirped grating when a maximum reverse bias voltage is applied to the left PN junction and a forward bias voltage is applied to the right PN junction. As observed, the 3-dB bandwidth of the spectra is increased largely, which is much larger than that of the uniform grating. By increasing the grating length and dividing the grating into more sections, the fabricated grating would have a better optical performance in terms of the group delay and chirp rate.

Conclusion

The programmable grating can find numerous applications. An application example is its use for programmable signal processing, in which three signal processing functions including temporal differentiation, true time delay, and microwave frequency identification have been demonstrated [12]. In fact, a programmable microwave signal processor based on a reconfigurable grating could perform other signal processing functions such as microwave filtering, temporal integration, and Hilbert transformation. In addition to its use in microwave signal processing, the programmable grating could also be employed for arbitrary microwave waveform generation. For example, it can be used as a spectral shaper to generate a chirped microwave waveform for radar and other imaging applications. An array of such gratings can also be used as a beamforming network to generate true time delays for wideband squint-free beam steering. By increasing the number of independent sub-grating sections, the functionalities of the signal processor could be further increased, and the performance could be enhanced.

In summary, thanks to the strong reconfigurability enabled by the three independently controllable PN junctions, an on-chip programmable grating was realized, capable of varying its index modulation profile by field programming to present diverse spectral characteristics. A phase-shifted, a uniform and a chirped grating have been demonstrated. Such a programmable grating device overcomes the long-standing limitation of conventional grating devices that have fixed modulation index profiles and presents overwhelming advantages in terms of strong and fast reconfigurability, compact size, and low power consumption.

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