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Waveguide-integrated photonic crystal spectrometer with camera readout

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We demonstrate an infrared spectrometer based on waveguide-coupled nanocavity filters in a planar photonic crystal structure. The input light is coupled into the waveguide, from which spectral components are dropped into the cavities and radiated off-chip for detection on a commercial InGaAs camera. The spectrometer has a footprint of only 60 μm by 8 μm . The spectral resolution is about 1 nm in the operation bandwidth of 1522–1545 nm. By substituting the membrane material and structure parameters, this design can be easily extended into the visible regime and developed for a variety of highly efficient, miniature photonic applications. © 2014 AIP Publishing LLC.

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Motivated by the need for compact, high-performance spectrographs, a wide variety of chip-integrated devices have been investigated, including microresonator arrays,^{1,2} photonic crystals (PhCs),^{3–5} and arrayed waveguide gratings (AWGs).⁶ For certain applications such as biochemical and environmental sensing,^{7,8} there has been an interest to develop planar spectrometers that scatter dispersed light out of the chip so that it can be imaged using simple imaging arrays such as cameras. Pervez *et al.*⁴ demonstrated a PhC grating pattern integrated into a slab waveguide, which could be imaged using a camera. The spectral resolution of this device reached $\Delta\lambda/\lambda \sim 0.1$ in the visible spectrum, where $\Delta\lambda$ is spectral resolution and λ is the central wavelength of operating range. Gan *et al.*³ addressed the spectral resolution problem by replacing the grating with an array of photonic crystal nanocavities that coupled light from the planar waveguide out of the plane into a camera. This approach improved the spectral resolution to $\Delta\lambda/\lambda \sim 4 \times 10^{-4}$ ($\sim 1 \times 10^{-4}$) in the visible (near-infrared) spectrum. However, both approaches suffered from a low efficiency since the incident photon flux was spread nearly uniformly across all spectral filters and each filter only scattered up a small portion of the spectrum towards the camera. In a linear waveguide, the photon flux can be guided along a series of spectral filters, so that every photon can, in principle, be directed into the spectrally matched output port. Thus, linear waveguides have been the basis of numerous in-plane spectral filters for wavelength detection.

Here, we demonstrate a spectrograph relying on a linear waveguide coupled to an array of cavities that direct the filtered field upward for detection with a camera, which greatly simplifies the mode of operation than its counterparts.^{9,10} This design provides both off-chip detection with standard cameras, high spectral resolution enabled by the cavity design, and high photon efficiency. Our device employs a PhC cavity array side-coupled to a line-defect waveguide with a total device efficiency of 6.36% and a spectral

resolution of $\Delta\lambda/\lambda \sim 6.5 \times 10^{-4}$. The device operates at a wavelength near 1550 nm with a bandwidth of 24 nm. By extending the number of nanocavities whose resonances fall into the bandgap of the line-defect waveguide, this type of waveguide-integrated spectrometer could allow hundreds of wavelength channels to be simultaneously monitored using an off-the-shelf camera.

As the scanning electron microscope (SEM) image shown in Fig. 1(a), the micro-scale spectrometer device consists of a line-defect waveguide in a triangular planar PhC lattice, side-coupled to 24 linear three-hole defect (L3) nanocavities.¹¹ The indices of C1–C24 are marked for each cavity and the cavity resonant modes are tuned by shifting of the end-holes of the L3 design: $\Delta s = 0.15a + 0.005a * (n - 1)$, where a is the lattice constant and n is the cavity index. The device was fabricated on a silicon-on-insulator (SOI) wafer with 200 nm thick silicon top membrane. The PhC structures are formed by a series of electron-beam lithography (EBL), dry etching, and wet chemical (hydrofluoric acid) undercutting of SiO₂ sacrificial layer under the membrane. The lattice constant of $a = 440$ nm and the hole radius $r = 0.29a$ were chosen to achieve a bandgap within the telecom band. To get a better bandgap overlapping between the line-defect waveguide and L3 cavities, two rows of the holes next to the waveguide were outwards shifted from the waveguide by $0.03a$, respectively. All cavities were 60° rotated and spaced by three lattices with respect to the waveguide axis to improve the coupling efficiency.¹² Meanwhile, we also introduced a series of perturbed holes in the vicinity of the cavity defect. These perturbed holes serve to shape the far-field radiation of the cavity modes to match a free space Gaussian mode, therefore increasing the out coupling of the cavities,¹³ as shown in the inset of Fig. 1(a). The resonant wavelengths of the cavities were gradually red-shifted by progressively shifting the L3 cavity end-holes outwards, achieving channel spacing of ~ 1 nm (~ 128 GHz)¹¹ for 24 cavities to span an operating range from 1522 to 1545 nm—well within the PhC lattice bandgap. Shown in Figs. 1(b)–1(d) are simulations of

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FIG. 1. (a) SEM image of the fabricated photonic crystal (PhC) chip, showing the 24 L3 nanocavities 60° tilted relative to the axis of the line-defect waveguide. All the cavities distribute in pairs to form 12 periods. Scale bar: $10\ \mu\text{m}$. Inset: magnified image of one period, a higher coupling efficiency between the line-defect waveguide and L3 cavities was realized by this configuration. (b)–(d) Simulated electric field intensity ($|E|^2$) distribution for three L3 nanocavities (C9, C11, and C12) excited by the line-defect waveguide's fundamental mode and the corresponding resonant wavelengths are 1527.3 nm for C9, 1529.1 nm for C11, and 1529.8 nm for C12, respectively.

the electric field intensities $|E|^2$ in a short device section containing three cavities (C9, C11, and C12) with resonant modes located across the spectrometer's spectrum at 1527.3 nm, 1529.1 nm, and 1529.8 nm, respectively; the full 24-cavity spectrometer devices was not simulated as a whole because of memory limitation to 16 GB. In these simulations, we first considered the fundamental line-defect waveguide mode at 1520 through 1550 nm in increments of 5 nm using an eigenmode solver, then propagated these modes through the waveguide-cavity section using finite-difference time-domain (FDTD) software. Because the modal dispersion in the range from 1520 to 1550 nm is small, with an index difference of 0.04 for the fundamental mode, we found it adequate to neglect differences in modal profile over the 5 nm windows. These simulations clearly show the wavelength-dependent excitation and outcoupling through the cavity modes, as expected. With optimized fabrication and pattern parameters, higher Q factors can be reached, resulting in a higher spectral resolution below 0.1 nm.^{9,11,14} Also, with precise tuning of lattice constant and a larger number of L3 nanocavities, this PhC structure can realize a controllable channel spacing and operation bandwidth.

The probe light is introduced into the line-defect waveguide through a coupling method (fiber taper coupling in this paper). The waveguided light then couples into the 24 PhC nanocavities and transmits out of plane selectively at

corresponding resonant wavelengths. Sweeping through the resonant wavelengths of all these cavities, the light is dispersed and filtered into a two-dimensional (2D) detector array. Monitoring the scattered light from each spatial position provides the spectral content of the input light, as shown in Fig. 2(a). We fabricated the fiber taper by pulling an infrared (IR) single mode fiber over a hydrogen flame. A controlled-stretch across 26 mm over a heat zone of 10 mm produced a fiber taper with diameter of $1\ \mu\text{m}$. The fiber taper is then precisely positioned on top of the line-defect waveguide. A polarization controller (PC) is used to optimize the coupling between the fiber and the TE mode of the PhC waveguide. The scattered light from each nanocavity is collected by an objective lens (NA = 0.55) and directed to either the 0.5 m long commercial spectrometer or an uncooled InGaAs camera (IRVista). The experimental setup for this demonstration is shown in Fig. 2(b). In Fig. 2(c), an optical image shows a fiber taper coupled with the line-defect waveguide of this device (#3: from top to bottom). A yellow box highlights the section where the fiber and waveguide are positioned together.

When the tapered fiber is optimally positioned on the PhC waveguide, we observe a marked drop in transmission for spectral components resonant with waveguide modes, as seen in Fig. 3(a). We infer from the transmission before and after placing the fiber on the waveguide that the fiber-to-waveguide

FIG. 2. (a) Schematic of the compact spectrometer based on L3 PhC nanocavities coupled with a line-defect waveguide, with the probe light coupled into the waveguide and decoded into many narrowband signals by cavity modes. (b) Confocal microscope setup used to characterize the device via the scattered signals from nanocavities. A broad or narrowband laser is coupled into the device and filtered by the cavities into narrowband (resonant) signals, which are detected by a commercial spectrometer or a Vista IR camera. HWP: half-wave plate, OL: objective lens, TF: tapered fiber, PC: polarization controller. (c) Optical image of the working device: a fiber taper coupled with the line-defect waveguide. Scale bar: $10\ \mu\text{m}$.

FIG. 3. (a) Transmission spectrum of the tapered fiber when coupled with the device. The broad dip results from the bandgap of the line-defect waveguide; the series of small dips are due to coupling into the cavity modes. (b) SEM image of one section of the device, scale bar: 2 μm . (c)–(e) Optical images of cavity transmission gotten from a narrowband laser and IR camera configuration: the laser wavelengths coincide with the resonances of C5, C6, and C7 cavities, respectively.

coupling efficiency (η_1) is 68%. The broad transmission drop from 1520 to 1545 nm corresponds to coupling to the PhC line-defect waveguide, while the multiple narrow dips correspond to additional loss via the waveguide-coupled nanocavities, as are also marked in the spectrum. After this broadband characterization, we switched the input light source to a tunable narrowband laser (5.6 fm linewidth) and recorded the cavity emission as a series of images on the IR camera. Figs. 3(c)–3(e) show spatially resolved images of three cavities (C5, C6, and C7) obtained when the laser was tuned to their resonant wavelengths of 1525.79 nm, 1527.28 nm, and 1528.15 nm, respectively. These corresponding cavities are indicated in the SEM image in Fig. 3(b). In each camera image, a bright spot with high contrast from other cavity regions comes from matching between the narrowband light and cavity resonance, which illustrates the function of the cavities as wavelength-selective channels. These sweeping results of narrowband light source demonstrate that the cavity array spectrometer enables spectral resolution equal to the bandwidth of the cavity modes. To obtain the spectrum of an unknown input field from such images, a calibration of the cavity emission to spectral components is required. In practical applications, it is necessary to attach the tapered fiber with the chip and make them a monolithic package. Our fiber taper is manipulated in ambient environment and is placed in contact with the silicon planar PhC waveguide. The contact of the tapered fiber is held

in place by surface forces. For packaging, the interface can be made robust by gluing the tapered fiber directly on the chip. In our current configuration, we have achieved a maximum of nearly 70% coupling efficiency from fiber to PhC waveguide. The efficiency can be further improved by engineering the diameter of the fibered taper for mode-matching with the photonic crystal waveguide. Alternatively, if the PhC waveguide is coupled with an on-chip silicon waveguide and an edge coupler, the off-chip coupling can be realized using only a single glued edge-coupling fiber (with coupling efficiency of 80%¹⁵). It is now commercially possible to couple to silicon photonic circuits with sub-dB losses using edge coupling or grating coupling. These couplers can be bonded into place to allow for stable operation of the device.

The spectral calibration can be obtained in two different configurations, which are illustrated in Fig. 4(a) for one of the cavities, C6. The top panel of Fig. 4(a) plots the reflection spectrum of the cavity (red line), which is obtained in a cross-polarized configuration¹⁶ by illuminating the cavity vertically from a free space objective with a broadband laser (0.95–2 μm) and measuring the reflection with a commercial IR spectrometer. This measurement indicates a Q factor of 1950. The transmission spectrum of the same cavity is obtained by exciting the cavity with a tunable narrowband ($\sim\text{MHz}$) laser source through the tapered fiber, PhC waveguide, and the cavity. The intensity of scattered light from

FIG. 4. (a) Reflection (red) and transmission (blue) spectra of C6 showing a resonance at 1527.28 nm. The reflection is obtained directly from the commercial spectrometer and the transmission spectrum is obtained by integrating the counts across the cavity region at multiple wavelengths, showing a good agreement. (b) Transmission spectra of the ten nanocavities (C1 ($Q = 1834.2$), C2 ($Q = 1958.7$), C4 ($Q = 1366.3$), C5 ($Q = 476.5$), C6 ($Q = 1868.9$), C9 ($Q = 766.2$), C12 ($Q = 1948.7$), C13 ($Q = 642.3$), C19 ($Q = 570.1$), C24 ($Q = 562.1$)) from the IR camera readout.

the cavity is collected using the IR camera. The resulting transmission spectrum is plotted in the bottom panel of Fig. 4(a), matching the reflectivity measurement in the top panel. Thus, an input spectrum can be measured by projection onto the drop cavities, which is detected using an off-chip camera. To make a general purpose spectrometer, the resonant wavelengths of the cavities would distribute uniformly and cover the whole spectrum of the target source. The spectra of ten of the L3 nanocavities are also sampled and summarized for a wider range of wavelengths, as shown in Fig. 4(b), indicating a linewidth of $\Delta\lambda \sim 1$ nm. The gradual Q drop of these cavities results from the increment of end-hole shifting from C1 to C24. This tuning mechanism unfortunately also changes the quality factor. To avoid this, a different tuning mechanism, e.g., incrementing the air hole diameters could be used to blue-shift cavities.¹⁷

The coupling of the cavities to the waveguide was designed to be in the critical coupling regime since this optimizes the efficiency. Using the measured cavity quality factors, we can estimate the experimental coupling coefficients using coupled mode theory.¹⁸ In the waveguide-cavity system, the side-coupled waveguide is treated as a perturbation for individual L3 cavities. We measured that the resonant mode of an unloaded cavity (far away from the waveguide) with optimal spacing of $\Delta s = 0.15a$ occurs at $\lambda_0 = 1525.8$ nm with $Q_0 = 1948.7$. This quality factor is limited by scattering, not material losses. When this cavity is coupled to the waveguide at a distance of $3a$, we measured a drop in the quality factor to $Q' = 778.9$ and a wavelength red-shift by $\Delta\lambda = 1.48$ nm to $\lambda' = 1527.28$ nm. The coupling efficiency from waveguide mode to free space mode through the cavity, η_2 , is estimated from coupled mode theory as $4\kappa_w\eta_{c-obj}\kappa_c/(\kappa_c + \kappa_w)^2 \approx 9.35\%$,^{18,19} where the cavity intrinsic loss $\kappa_c = \omega_0/Q_0$ is 0.63 THz, the loss rate into the waveguide $\kappa_w = \omega'/Q' - \omega_0/Q_0$ is 0.95 THz, and η_{c-obj} is the coupling efficiency of the cavity mode into the imaging objective mode. From the far-field emission of the L3 mode profile, η_{c-obj} is calculated by the integral over the sub-critical solid angle defined by the NA of the objective lens, yielding $\eta_{c-obj} \sim 10\%$.^{20,21} This coupling efficiency of the cavity mode towards the objective can be increased by employing cavity designs with tailored radiation patterns.^{13,21} The total device efficiency $\eta_1 \times \eta_2 \approx 6.36\%$. This efficiency could be further improved if the coupling from the tapered fiber to the PhC waveguide is optimized; nearly 100% coupling has been demonstrated previously using such a tapered fiber coupling approach.²² In addition, the coupling from the L3 cavity modes to a free space objective can be as high as 28% using an objective with NA = 0.75.²¹ With these optimizations, the overall efficiency of our device could be as high as 28%, which is with a factor of two of a commercial grating-based spectrometer. Because of the broad transmission range of Si, this spectroscopy can be extended to longer wavelengths into the mid-infrared.

In conclusion, we have demonstrated a compact, flexible, and economical spectrometer based on 24 L3 nanocavities side-coupled with a PhC line-defect waveguide. Spectral components of waveguide-coupled input light are filtered through these cavities and emitted to a camera for detection. Using a tapered fiber to introduce light into the

line-defect waveguide, 6.36% device efficiency is obtained. Within the 1520–1545 nm range, spectral resolution of 1 nm at 1527 nm was realized at a footprint of $60\ \mu\text{m}$ by $8\ \mu\text{m}$. With the improvement of fabrication process and structural parameters, higher resolution, uniform channel spacing, and broader operation bandwidth are possible. Integrated with the same detector array and calibrated from spatial to spectral mapping, this packaged on-chip spectrometer can find a wide application in spectroscopy analysis.

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