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A grating coupler with a trapezoidal-hole array was designed and fabricated for perfectly vertical light coupling between a single-mode optical fiber and a silicon waveguide on a silicon-on-insulator (SOI) substrate. The grating coupler with an efficiency of 53% was computationally designed at a 1.1-μm-thick buried oxide (BOX) layer. The grating coupler and the silicon waveguide were fabricated on the SOI substrate with a 3.0-μm-thick BOX layer with a single full-etch process. The measured coupling efficiency was 24% for TE-polarized light at 1528 nm wavelength, which was 0.69 times of the calculated coupling efficiency for the 3.0-μm-thick BOX layer.

Silicon-on-insulator (SOI) is an attractive platform for silicon photonic integrated circuits (PICs), such as ultra-small optical switches, wavelength-division multiplexers, optical modulators and so on.[1,2] A typical thickness of a silicon slab-waveguide is sub-micrometers, which is much smaller than the diameter of a single-mode optical fiber. Efficient light coupling between the single mode optical fiber and the silicon waveguide is an important issue for PICs. Grating couplers with small footprints are suitable for PICs because a number of optical fibers can be mounted on the planer PIC. Several types of grating couplers were proposed and demonstrated for efficient light coupling.[3-8]

Most of high efficient grating couplers are used for optical fibers tilted from the vertical to the planar PICs.[3-5, 7] The phase matching condition between propagation modes of the planer waveguide and the optical fiber is satisfied precisely by adjusting the tilt angle of the optical fiber. On the other hand, vertical grating couplers are more convenient for mounting a number of optical fibers on PICs, though the phase matching condition cannot be satisfied by adjusting the tilt angle of the optical fiber. If the grating profile is symmetry with respect to the vertical, the maximum coupling efficiency does not exceed 50%. Asymmetric grating are needed for efficient light coupling.

Various asymmetric-grating couplers were proposed for the vertical incidence. D. Taillaert designed a grating coupler with a Bragg reflector on one side of the grating.[6] The maximum coupling efficiency was 41%. But the Bragg reflector made the full width at half maximum (FWHM) of coupling efficiency spectrum very narrow, which was not suitable for wideband light coupling. An asymmetrical groove profile, such as a saw-tooth profile, improves the coupling efficiency for the vertical incidence. Z. Liang et al, designed a multilevel stair-step grating, but it was for 10° oblique incidence.[7] F. V. Laere, et al, designed and fabricated a grating coupler with parallelogram grooves, i.e., a slanted grating.[8] The designed coupling efficiency was 59%, but the measured efficiency was 16%. The saw-tooth grooves and the parallelogram grooves are not easy to be fabricated presicely.[9, 10]

A grating consisting only of rectangular grooves with a uniform depth, which is called a “binary grating”, might be a candidate for the vertical incident grating coupler. The rectangular grooves are easy to be fabricated with mature lithography and etching techniques. In the case of a subwavelength period grating, the effective refractive index of the grating can be controlled with fill factors of grooves. A high efficiency diffraction grating was achieved by modulating the fill factor of grating grooves.[11] J. Yang et al, designed a subwavelength-period binary grating coupler for the vertical incidence of light into a SOI waveguide.[12] The calculated coupling efficiency was 69%. W. Zhou et al, designed a high efficient fully-etched binary grating coupler for the vertical incidence.[13] Since the groove depth was equal to the thickness of the waveguide, the grating coupler and the silicon waveguide can be fabricated simultaneously in the top silicon layer of a SOI substrate with a single full-etch process. However, the modulated binary grating coupler is not easy to be fabricated because their designed grating grooves are extremely narrow and deep such as 50-nm-wide and 200-nm-deep.

A two-dimensional array consisting of asymmetric holes is the other candidate for a high efficient grating coupler. K. Qin et al, designed the grating coupler consisting of fully etched triangle-holes for a 12° oblique incidence, not for the vertical incidence. The calculated coupling efficiency was 53%.[14] Asymmetry of the triangle holes improves the diffraction efficiency. The triangle-hole array grating did not contain extremely small and deep holes.

In this study, a grating coupler of trapezoidal-hole array was designed and fabricated for the perfectly vertical mounting of a single-mode optical fiber. The trapezoidal holes are easy to be fabricated because the corners of the trapezoidal holes do not have sharp acute angles. Moreover, the trapezoidal holes improved the coupling efficiency, compared with the triangle-holes. The physical mechanism for improving the coupling efficiency was made clear with numerical simulations of electromagnetic fields. The grating coupler and the waveguide were fabricated in the top silicon layer of the SOI substrate with a single etching process. The trapezoidal holes were fully etched through the top silicon layer. To the best of our knowledge, this study is the first experimental demonstrations not only of the trapezoidal-hole array grating coupler but also of the triangle-hole array grating coupler.

Figure 1 (a) shows a schematic of the grating coupler consisting of trapezoidal holes for the vertical coupling with a single mode optical fiber. The 250-nm-thick top silicon layer of the SOI substrate acts as the grating coupler and a waveguide. The lattice of the hole-array grating is rectangular. The holes are isosceles-trapezoidal. The hole depth is 250 nm which is the same as the thickness of the top silicon layer. The light wave diffracted by the grating is guided by the 13-μm-wide silicon slab waveguide.

By using the electromagnetic numerical simulation with three-dimensional finite difference time-domain (3D-FDTD) method,[15] the grating periods and the sizes of the trapezoidal holes were optimized for the infinitely thick buried-oxide (BOX) layer to obtain the highest coupling efficiency at 1550 nm wavelength. The incident light beam was a TE-polarized Gaussian beam with a 10-μm beam diameter. Unit cell of the optimized trapezoidal holes is shown in Fig. 1(b). The Particle swarm optimization was used for the optimal design[16]. A periodic boundary condition was adopted in the *y* direction. The light wave reflected by an interface between the buried oxide (BOX) layer and the bottom silicon substrate was excluded. The grating periods and the hole sizes were designed in increments of 10 nm because of the data-resolution of EB lithography system (Elionix Co., Ltd., ELS-7500EX). The optimized grating pitches were 660 nm in the x direction and 690 nm in the y direction. The height and bases of isosceles-trapezoids were 500 nm, 220 nm and 350 nm, respectively. The fill factor which was defined as an area ratio of the open of hole to the unit cell of the lattice was 0.31. The dimensions of the hole array were 18 in the x direction and 17 in the y direction, so that the grating area was 11.8×11.7 μm^2.

Calculated coupling efficiency of the trapezoidal-hole array grating is shown as the red curve in Fig. 2. The maximum coupling efficiency was 41% at 1550 nm wavelength. The FWHM of the efficiency spectrum was 57 nm, which is comparable with that of the conventional grating coupler.[3)] The grating pitch in the y direction, 690 nm, is too long to generate only the zero order diffracted wave as a result of optimization of the grating pitches and hole-shape for the 13-μm wide waveguide. The ±1st order diffracted waves are also generated and propagate in the 13-μm-wide silicon waveguide. The dashed red curve in Fig. 2 is the calculated coupling efficiency only for the zero-order wave. The maximum coupling efficiency was 30%.

A grating coupler consisting of isosceles-triangle holes was also designed for the sake of comparison. The designed hole shape is shown in Fig. 1(c). The grating pitches were 620 nm in the x direction and 500 nm in the y direction. The height and base of triangles were 480 nm and 220 nm, respectively. The dimensions of the hole array were 18 in the x direction and 21 in the y direction. The triangle holes had vertices with sharp acute angles and the area filling factor was 0.17. The triangle holes are not easy to be fabricated accurately, compared to the fabrication of the trapezoidal holes. The calculated coupling efficiency of the triangle-hole array grating is shown as the blue curve in Fig. 2. The maximum coupling efficiency was 34%. Moreover, the FWHM of coupling spectrum was reduced. The dashed blue curve in the figure was the coupling efficiency only for the zero-order wave in the silicon waveguide, which is the same as the blue curve. The grating pitch in the y direction is short enough not to generate the higher order diffracted wave, although the optimization was made for the 13-μm wide waveguide. It is mentioned that the FWHM of the efficiency spectrum of the trapezoidal-hole array is still wider than that of the triangle-hole array.

The area fill factors of the trapezoidal and triangle hole arrays were 0.31 and 0.17, respectively. A large fill-factor makes an index modulation of the grating deep. Therefore, it is reasonable that the coupling efficiency of the trapezoidal-hole array is higher than that of the triangular-hole array. Why was the fill factor of the optimized triangle holes less than that of the trapezoidal holes? Figure 3 shows close-up views of time-averaged squares of the *y*-components of the electric fields in the grating couplers for trapezoidal and triangle hole arrays, respectively. The light energy flows in the +*x* direction. The light energy in the trapezoidal-hole array mainly flows in the channels among the holes. In the case of the triangle-hole array, there are no noticeable light energy flows in the channels among the trapezoidal holes, and intense electric fields appear in the triangle holes especially near the sharp acute angles. The light waves are reflected at bases of the isosceles triangles, so that the standing wave grows in the array. In order to make the fill factor large for obtaining higher efficiency, the triangle bases must be longer. But the longer triangle-bases do not contribute to improve the coupling efficiency, because the long triangle bases increase the reflection of light at the bases. This is the reason that the fill factor of the optimized triangle-hole array is less than that of the trapezoidal holes array.

The hole-array gratings shown in Fig. 1 were designed for the infinitely thick BOX layer. The BOX layer of SOI substrate is a few micrometers thick. The light wave which partially transmits through the hole array grating is reflected at the interface between the BOX layer and the silicon substrate. The reflected light wave also couples into the silicon waveguide by the grating coupler. The total coupling efficiency depends on the thickness of the BOX layer because of the interference of light. This is called the bottom mirror effect.[17)] The thickness of the BOX layer was determined for the constructive interference. Figure 4 shows the calculated coupling efficiencies as a function of the thickness of the BOX layer. The wavelength of light was 1550 nm. The maximum coupling efficiency of the trapezoidal hole array was 53% at the thicknesses of 1.1 μm, 1.6 μm, 2.1 μm, and 2.7 μm. The maximum efficiency of triangle hole array was 44% at the thicknesses of 1.0 μm, 1.6 μm, 2.1 μm, and 2.7 μm. The maximum coupling efficiencies are higher than those for the infinitely thick BOX layer shown in Fig. 2. Moreover the maximum efficiency of the trapezoidal hole array is comparable to the efficiency of a fully-etched binary grating coupler for the slanted incident light. [13)]

Input-and-output grating couplers with the trapezoidal-hole array was fabricated on a SOI substrate. The input and output grating couplers were connected to each other with a 13-μm-wide and 1.0-mm-long silicon waveguide. The top silicon layer was 250-nm-thick, and the BOX layer was 3.0-μm-thick. The authors could not prepare the SOI substrate with the 1.1-μm-thick BOX layer. Although the 3.0-μm-thick BOX layer is not for the constructive interference, the light coupling can be demonstrated. The calculated coupling efficiency for the 3.0-μm-thickness is 29 %.

The input-and-output grating couplers were fabricated with the techniques of electron-beam lithography and reactive ion etching (RIE). The grating couplers with the connecting waveguide were formed simultaneously on the SOI substrate with one lithography-and-etching process. Figure 5 shows scanning electron micrographs of the fabricated input grating coupler with the waveguide. The grating pitches in the *x* and *y* directions are the same as the design. The trapezoidal holes were slightly larger than the design sizes. Corners of the trapezoidal holes were rounded with a radius of about 20 nm because of the proximity effect in the EB lithography.

Input and output optical fibers for measuring the coupling efficiency were vertically mounted on the fabricated grating couplers. The input optical fiber was a single-mode polarization maintaining optical fiber. The TE polarized light emitted from a wavelength-tunable laser diode (New Focus Corp., Velocity 6328 Tunable Laser) was guided onto the input grating coupler by the input optical fiber. The tunable range of laser wavelength was from 1520 to 1570 nm. The light beam from the output grating coupler was guided by a single-mode optical fiber, which was connected to the photodetector (Newport Corp., 918D-IR-OD3). Total transmittance of the input and output grating couplers with the connecting waveguide was measured from a ratio of the output power of the output optical fiber to the output power of the input optical fiber. A coupling efficiency of the grating coupler was evaluated from the square root of the total transmittance under the assumptions that the coupling efficiencies of the input and output grating couplers were equal to each other and the light wave transmitted in the connecting waveguide without propagation loss.

The measured coupling efficiency spectrum is shown as the blue curve in Fig. 6. The maximum coupling efficiency of the fitted curve to the measured data was 24% at a wavelength of 1528 nm. The red curve is the calculated coupling efficiency of the designed grating for the 3.0-μm thick BOX layer. The measured maximum coupling efficiency was 0.77 times of that of the design, and the measured peak wavelength was shorter than that of the design by 12 nm.

The shift of the peak wavelength was due to the fabrication error of the grating coupler. The green curve is the coupling efficiency calculated from the sizes of the fabricated trapezoidal holes. Each dimension was acquired from the scanning electron micrograph in Fig. 5. The peak wavelength of the dashed curve was shifted to shorter wavelength, which was in good agreement with the measured peak wavelength. Each corner of the trapezoidal holes had a 20-nm radius of curvature. But the small roundness of the corners does not influence the coupling efficiency significantly.

The maximum coupling efficiency of the green curve was 34%, which was about 1.4 times higher than the measured maximum efficiencies. Light scattering due to the side-wall roughness of the connecting waveguide and adjustment errors of the optical fibers are possible causes of the decrease in the coupling efficiency. The coupling loss due to the adjustment errors were evaluated by experiments and numerical simulations. For example 4-μm alignment error in the longitudinal direction of the waveguide and 2-μm alignment error in the lateral direction caused the coupling loss of 1 dB, respectively.

The BOX layer of the fabricated grating coupler was 3.0-μm-thick. The optimum thicknesses of the BOX layer were 1.1 μm, 1.6 μm, 2.1 μm, and 2.7 μm for constructive interference. If the BOX layer had the optimum thicknesses, the coupling efficiency of 38% can be expected from the product of the calculated maximum efficiency of 53% and the experimental loss of 1/1.4.

In conclusion, the grating coupler consisting of trapezoidal holes was designed for the vertical light coupling with a single-mode optical fiber. The grating coupler with a 250-nm-thick silicon waveguide on the 1.1-μm-thick BOX layer was designed. The calculated maximum coupling efficiency was 53% at a wavelength of 1550 nm. The grating couplers were fabricated on the 250-nm-thick top silicon layer on the 3.0-μm thick BOX layer. The grating couplers and the silicon waveguide were simultaneously fabricated with a single full-etch process. The measured maximum coupling efficiency was 24% at a wavelength of 1528 nm, which was 1/1.4 of the calculated coupling efficiency of the grating coupler with the 3.0-μm thick BOX layer. From this experimental result, the coupling efficiency of 38% was expected for the 1.1 μm-thick BOX layer.

Acknowledgments

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Figure Captions

Fig. 1. A hole-array grating coupler between a vertically mounted optical fiber and a silicon slab waveguide on a SOI substrate. The grating coupler consists of a two-dimensional array of through-holes in the top silicon layer with a thickness of 250 nm. (a) Unit cell of the optimally designed trapezoidal-hole array. (b) Unit cell of the optimally designed triangle-hole array. These unit cells were designed for the infinitely thick BOX layer.

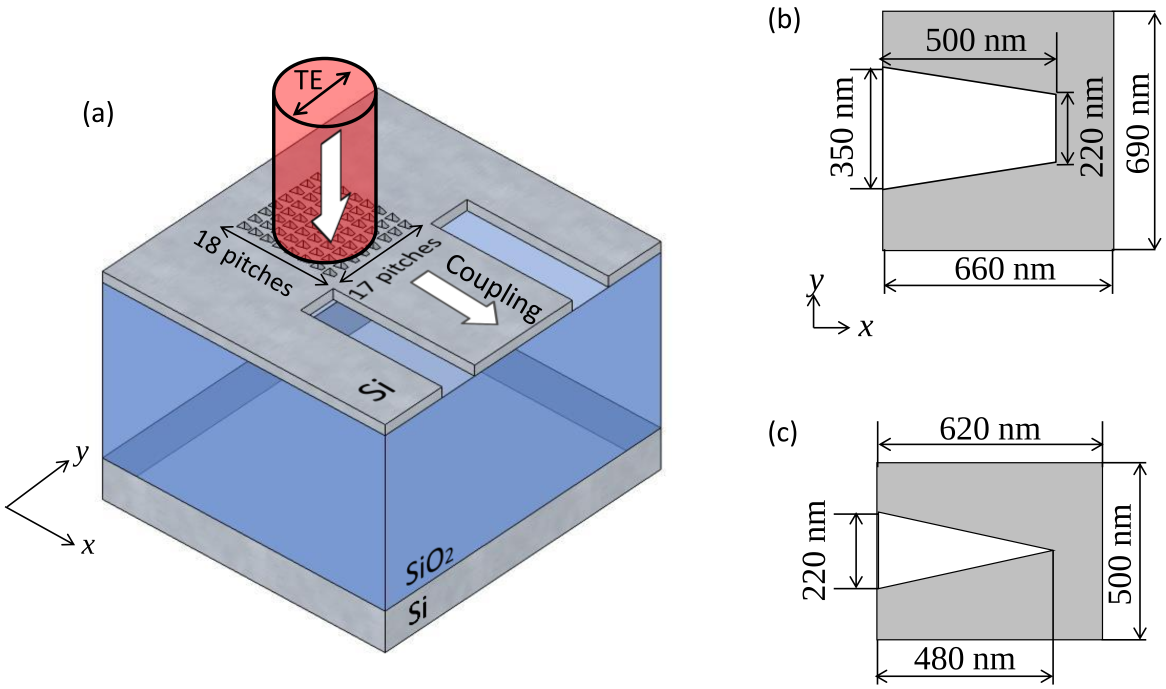
Fig. 2. Calculated coupling efficiencies as a function of wavelength of the incident light for the optimized trapezoidal-hole array and the triangle-hole array. Dashed curves are calculated coupling efficiencies only for the zero-order diffracted waves.

Fig. 3. Calculated distributions of the time-averaged square of *y*-component of the electric fields in the gratings. (a) The trapezoidal hole array, and (b) the triangle hole array.

Fig. 4. Calculated coupling efficiencies as a function of thickness of the BOX layer for the optimized trapezoidal-hole array and the triangle-hole array. The wavelength of the incident light is 1550 nm.

Fig. 5. Scanning electron micrographs of the fabricated trapezoidal-hole grating coupler. (a) The grating coupler with a 13 μm wide slab waveguide. The grating consists of 18×17 holes. The white solid circle indicates the core size of the input optical fiber. (b) Enlarged views of the trapezoidal holes. The hole sizes were acquired from the micrograph.

Fig. 6. Measured coupling efficiency as a function of wavelength. The measured maximum efficiency was 24% at a wavelength of 1528 nm. The red curve is the calculated efficiency of the optimized design for the 3.0-μm-thick BOX layer. The green curve is the efficiency calculated from the hole-size and pitches acquired from the SEM image of the fabricated grating.



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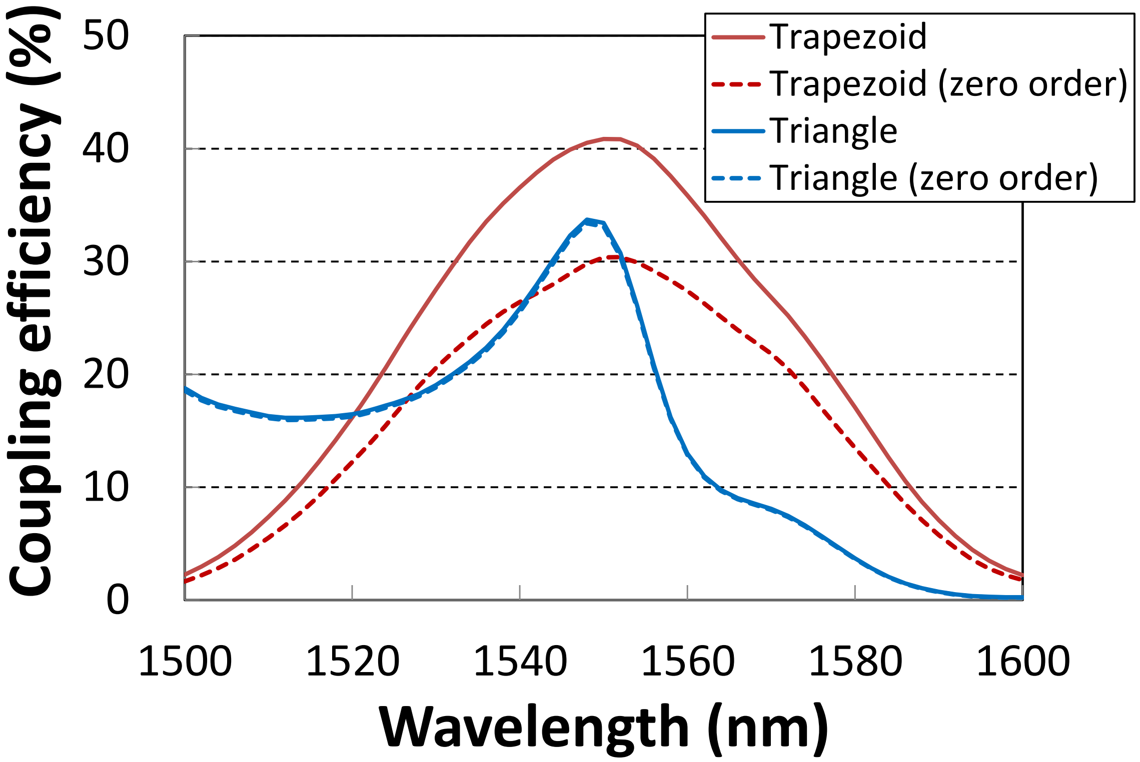

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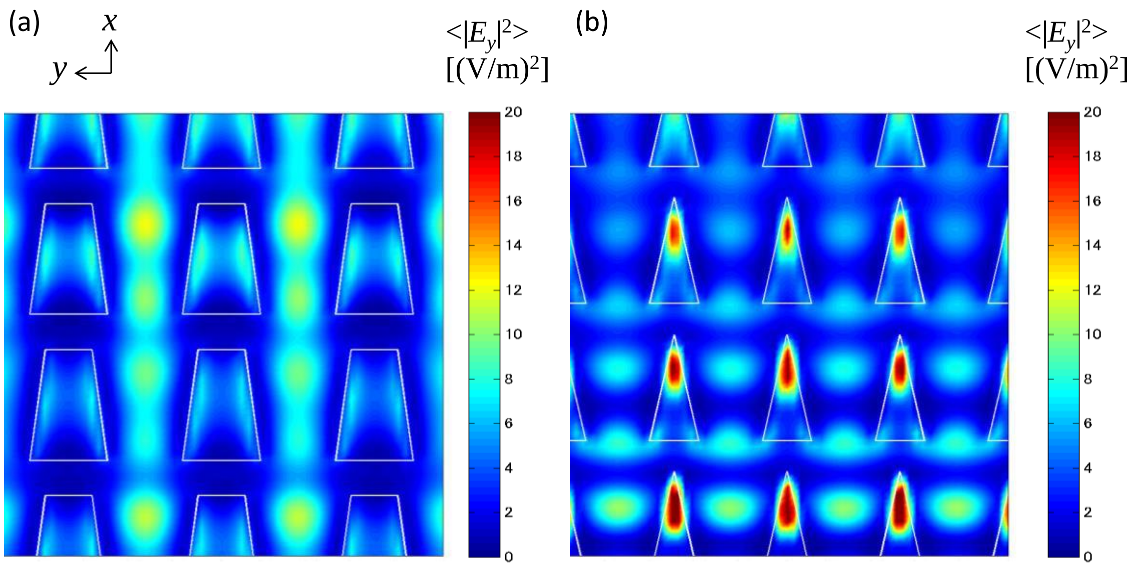

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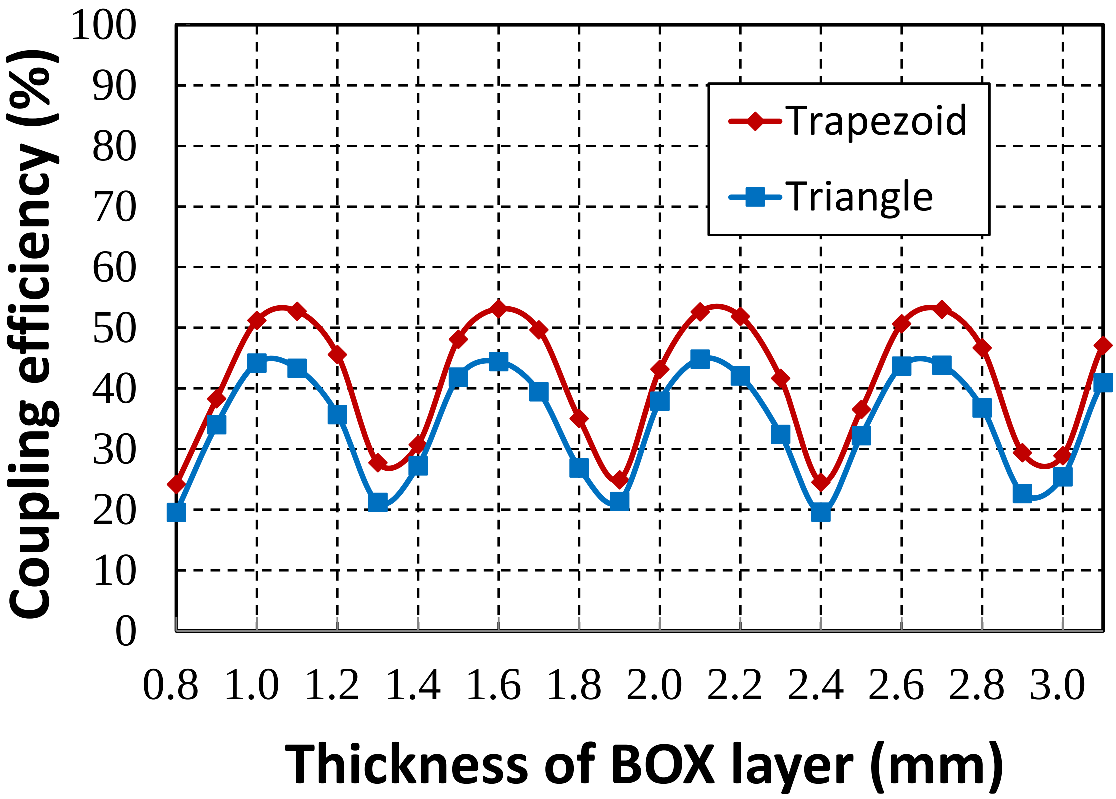

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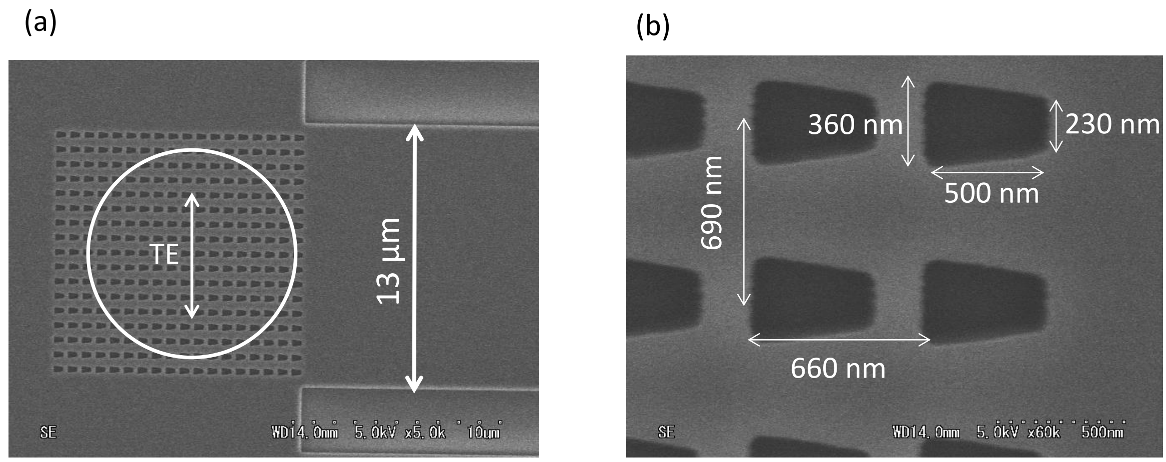

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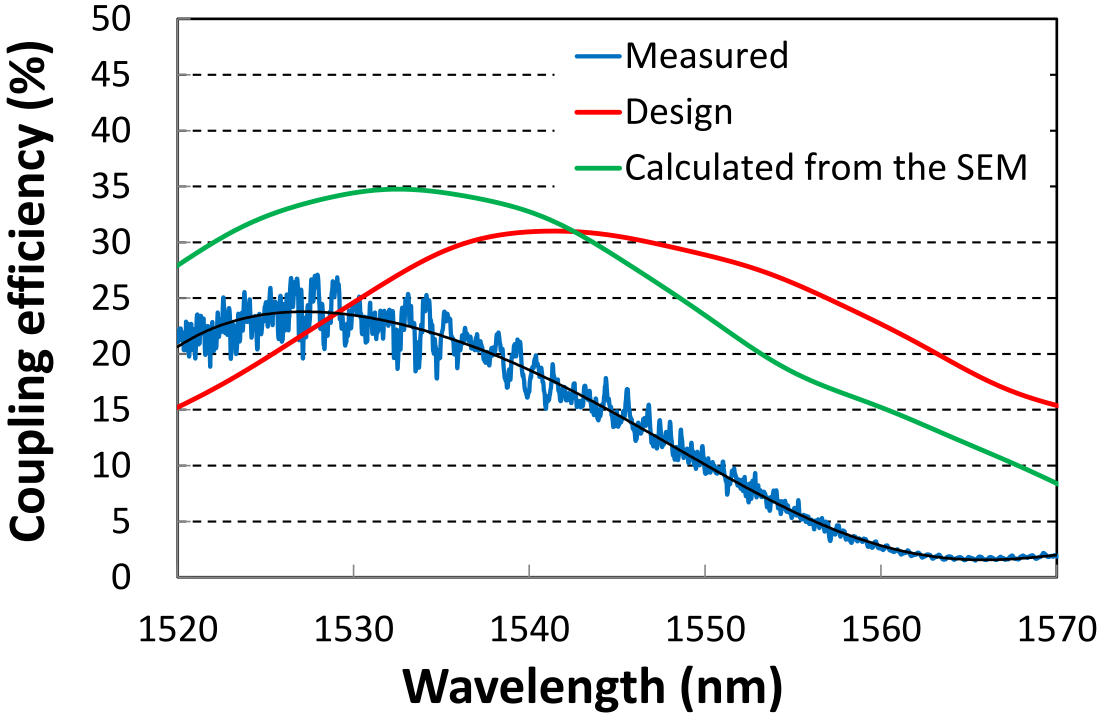

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