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We numerically investigate the attractive optical force between a suspended one-dimensional periodic photonic crystal waveguide and underlying substrate in a silicon-on-insulator platform. We show that the optical force is enhanced by designing the waveguide cross section to make the mode approach the band edge or substrate light line. We show that for periodic waveguides, the optical force is nonmonotonic with waveguide-substrate separation. This effect may enable the design of compact, integrated optical power limiters. © 2010 American Institute of Physics. [doi:10.1063/1.3493658]

In the past few years, intense research has been carried out on optical forces induced by the strongly enhanced gradient of the electromagnetic field close to micro- and nanophotonic devices.^{1–11} The forces provide a way to reconfigure microphotonic elements with experimentally measurable deflection.^{12–14} This mechanical actuation allows a number of important device functionalities, such as all-optically controlled filters,¹⁵ wavelength routers,¹⁶ and polarization rotators,¹⁷ as well as optomechanical Kerr effects.¹⁸ One structure that is particularly amenable to fabrication is a suspended, microbridge waveguide over a substrate.¹⁹ For appropriately designed devices, it has been predicted and verified experimentally that the optical force is dominant over other effects, such as thermo-optical effects, Casimir, and van der Waals forces.^{19,20} Previous theoretical and experimental work has demonstrated that light traveling through an unpatterned waveguide induces an attractive optical force between the waveguide and substrate.^{19,21} Introducing a periodic pattern into the waveguide to form a one-dimensional (1D)-periodic photonic crystal should introduce additional flexibility in tuning the behavior of the optical force.

Here we numerically investigate the effects of periodicity on optical forces between a microphotonic waveguide and substrate. While previous work has analyzed 1D-periodic photonic crystal microcavities,^{22,23} we consider light propagation in the pass band of a 1D-periodic photonic crystal. We show that the optical force on a 1D-periodic photonic crystal waveguide is enhanced due to several different physical effects as follows: delocalization near the substrate light line, effective reduction in the waveguide refractive index, and slow-light enhancement near the band gap. We find that, in contrast to unpatterned waveguides, the optical force shows a nonmonotonic dependence with waveguide-substrate separation. The force behavior near the photonic band edge may enable the design of optical switches that transmit only below a certain power threshold, i.e., power limiters.

We investigate the optical force between a patterned, 1D-periodic photonic crystal silicon waveguide and an underlying silica substrate, as shown in Fig. 1(a). In the paper, the physical wavelength is fixed to 1550 nm. We assume one

period of the waveguide is a cube of side length a with a circular air hole of radius $r=0.3a$. The modes of the waveguide-substrate system can be characterized as even or odd with respect to the mirror plane at $y=0$, according to the symmetry of the vector field.²⁴ We refer to the y -even mode as TM; the electric field is primarily in the z -direction. We refer to the y -odd mode as TE; the electric field is primarily in the y -direction.

In Fig. 1(b), we plot the dispersion curves for the two lowest TM bands and the lowest TE band. The two lowest TM bands are separated by a band gap. For TE polarization, the second lowest band does not couple strongly to a linearly polarized source and is not shown in the figure. We use the MIT PHOTONIC BANDS PACKAGE (Ref. 25) to calculate the full vectorial electromagnetic fields for one period of the infinite structure. From the fields, we calculate the force using the Maxwell stress tensor.²⁶ We plot the force per unit length per unit power ($F/L/P$), where we assume $P=Uv_g/L$. v_g is the group velocity, and U is the electromagnetic field energy.² We confine our calculation to the values of the period a for which the modes are guided [lie below the gray region in Fig. 1(b)]. All three of the modes shown give rise to an attractive optical force.

Figure 2(a) shows force per unit length per unit power as a function of the side length a for the TM modes (blue

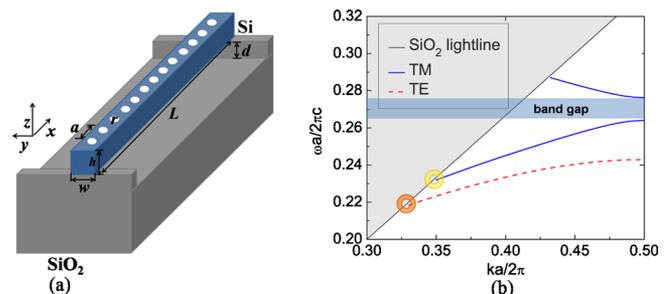


FIG. 1. (Color online) (a) Patterned, 1D-periodic photonic crystal Si waveguide with period a is separated from the SiO_2 substrate by a distance $d=100$ nm. r is the hole radius. (b) Dispersion relation for TM (solid curve) and TE (dashed curve) modes in waveguide with $r=0.3a$, and $h=w=a$. The dark region shows the substrate light cone. The point where the TE/TM mode crosses the light line is indicated by a circle.

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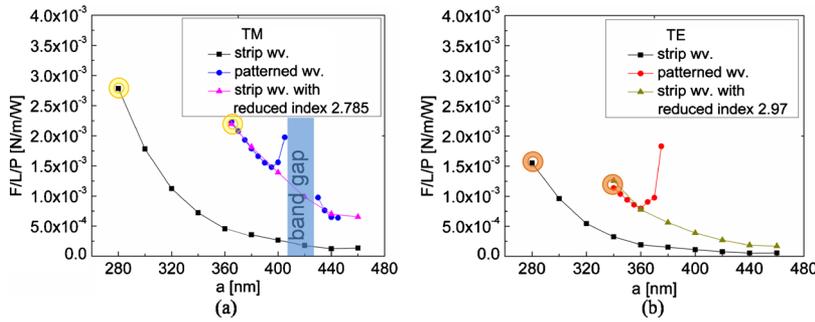


FIG. 2. (Color online) The attractive force per length per unit power as a function of period a for (a) TM and (b) TE modes at wavelength $\lambda=1550$ nm. One period of the waveguide (wv.) is a cube of side length a with a circular air hole of radius $r=0.3a$. The separation d between the suspended waveguide and substrate is 100 nm.

circles). The waveguide-substrate separation $d=100$ nm. The yellow circle indicates the value of a (~ 365 nm) for which the TM mode enters the light line. The blue box indicates the range of a for which 1550 nm light falls within the band gap of the TM modes. In this range, no light can propagate along the waveguide, and thus, no optical force is induced. We observe from the figure that the force increases near the light line and near the band edge. To understand these trends, we plot the force for an unpatterned strip waveguide with the same dimensions but no air holes (black squares). For the strip waveguide, the mode crosses the light line at a value of $a \sim 280$ nm, shown by the yellow circle. Like the patterned waveguide, the force increases as the mode approaches the light line, due to stronger coupling between the waveguide and substrate. Overall, the force curve for the patterned waveguide is shifted to the right with respect to the strip waveguide. This effect can be interpreted as a reduction in the effective index due to the air holes. We plot the force curve for a strip waveguide with reduced index equal to 2.79 with pink triangles. Away from the band gap, the force curve for the patterned waveguide follows that of the reduced-index waveguide. Near the band gap, the enhancement of force can be interpreted as a slow-light effect.¹ For fixed power, the energy in the mode increases proportionally to $1/v_g$, where v_g is the group velocity. Since the force is proportional to mode energy, the force per length per unit power goes to infinity for an ideal slow-light waveguide.

We plot the force for TE modes for values of a between 340 and 375 nm in Fig. 2(b). The light wavelength is 1550 nm. As for TM light, the force is enhanced near the light line and band edge. Away from the slow-light region, the force curve follows that of a strip waveguide with reduced refractive index equal to 2.97 (green triangles).

We next consider the dependence of the force on the waveguide-substrate separation, d . In a conventional strip waveguide, the force increases monotonically with decreasing distance.¹⁹ In the patterned waveguide, however, a change in distance can move a mode in or out of the photonic band gap, yielding quite different force behavior.

We consider a waveguide with $a=428$ nm. From Fig. 2(a), we can infer that the TM mode lies just above the band gap for $d=100$ nm. We plot the force as a function of separation in Fig. 3(a) (blue triangles). The force initially decreases with increasing distance, then increases as the mode approaches the band edge. For $d > 120$ nm, the mode lies in the band gap. The transmission, and thus force, are zero.

For a waveguide with $a=408$ nm, we can see from Fig. 2(a) that the mode lies just below the band gap for $d=100$ nm. The force (red circles) is zero for distances below ~ 80 nm, where the mode falls into the band gap, and decreases as a function of distance for $d > 80$ nm. The behavior should allow the design of an optical power limiter. If the device is designed with an initial waveguide-substrate distance > 80 nm, light can be transmitted through the waveguide. As the optical power is increased, the optical force will attract the waveguide to the substrate more strongly. In the center of the double-clamped waveguide, where the displacement is largest, the local mode will approach or enter the band gap, resulting in reflection, and reducing the transmitted power.

Figure 3(b) gives the force induced by near band edge TE light for a waveguide with $a=376$ nm. When a is less than 60 nm, the fundamental mode is no longer guided, and we set the force to zero. While non-negligible force values may be obtained for leaky modes with long propagation lengths, the force will decay as a function of length along the waveguide.

The displacement can be obtained from the calculated force values in Fig. 3 using the analytical expression $u_m = FL^3/32Ewh^3$ for a doubly-clamped beam,²⁷ where E is Young's modulus for bulk silicon. For a 60- μm -long beam with cross section 376×376 nm², if the waveguide-substrate separation is 100 nm, TE-polarized light with power $P=50$ mW results in a $F/L/P$ of 2.8×10^{-3} , and the displacement at the center of the waveguide is estimated to be 14.3 nm. We have verified using COMSOL finite element simulations that the displacement of the waveguide with hole radius $r=112.8$ nm is 15 nm. The discrepancy is likely due

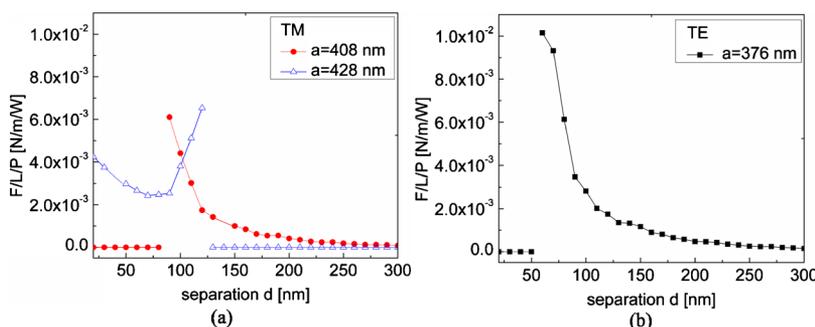


FIG. 3. (Color online) The attractive force per length per unit power as a function of distance d for (a) TM and (b) TE modes at wavelength $\lambda=1550$ nm.

to the fact that the holes modify the beam flexibility.²⁸

In conclusion, we have studied the attractive optical force between a 1D-periodic photonic crystal waveguide and underlying silica substrate. The optical force increases as the mode approaches the light line, as for an unpatterned strip waveguide. However, the periodicity introduces two additional mechanisms for enhancing the force as follows: reduction in the waveguide effective index and slow light enhancement near the band edge. Moreover, the shift in the waveguide mode in and out of the band gap with changes in waveguide-substrate separation give rise to nonmonotonic force behavior and may enable compact optical power limiters. It is intriguing to consider whether optomechanical coupling can be used more widely to tailor optical power response. The coupling of dielectric waveguides to substrates with loss or gain, incorporating plasmonic or quantum-confined structures, may enable a variety of devices to tailor power response, such as threshold-activated switches, which only transmit above a certain power, or power regulators, which self-adjust to maintain the output transmission within a specified range.

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