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REVIEW ARTICLE

Novel optoelectronic characteristics from manipulating general energy-bands by nanostructures

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Abstract This paper summarizes our research work on optoelectronic devices with nanostructures. It was indicated that by manipulating so called “general energy-bands” of fundamental particles or quasi-particles, such as photon, phonon, and surface plasmon polariton (SPP), novel optoelectronic characteristics can be obtained, which results in a series of new functional devices. A silicon based optical switch with an extremely broadband of 24 nm and an ultra-compact (8 μm × 17.6 μm) footprint was demonstrated with a photonic crystal slow light waveguides. By proposing a nanobeam based hetero optomechanical crystal, a high phonon frequency of 5.66 GHz was realized experimentally. Also, we observed and verified a novel effect of two-surface-plasmon-absorption (TSPA), and realized diffraction-limit-overcoming photolithography with resolution of ~1/11 of the exposure wavelength.

Keywords photonic crystal waveguide (PCWG), optomechanical crystal, surface plasmon polariton (SPP), two-surface-plasmon-absorption (TSPA)

1 Introduction

All the optoelectronic devices operate based on the interaction between light and matter. The emergence of the next-generation optoelectronic devices depends on our understanding and discovering of new machanism of the light-matter interaction. In the last decades or so, a great deal of research and development work has been carried out on the nanophotonics and demonstrated a lot of novel optoelectronic charateristics. It is necessary to go beyond individual devices and search for a more general rule behind each device and phenomenon. In analogy to the energy-bands of electrons, the energy-momentum relations of other fundamental particles (such as photons), quasi-particles (such as phonons), and polaritons, which are the couple systems among these particles, can be considered as “general energy-bands”. One of the essences of the novel optoelectronic charateristics in nanostructure lies in the ability to manipulate this kind of general energy-bands of various fundamental particles and their associated quasi-particles.

This paper summarizes our research work on nanophotonics from the perspective of general energy-bands manipulation. Here the general energy-bands of photon, phonon, and surface plasmon polariton (SPP) were manipulated by different nanostructures for realizing novel optoelectronic characteristics. Utilizing the mini-stop-band (MSB) with slow light effect in photonic crystal waveguide (PCWG), which was obtained by engineering the general energy-bands of photon, we realized silicon based optical switch with an extremely broadband of 24 nm and an ultra-compact (8 μm × 17 μm) footprint. The extinction ratio of as high as 15 dB was demonstrated over the entire bandwidth [1]. Through carefully designing the general energy-bands of both photon and phonon with a nanobeam based hetero optomechanical crystal, a very high phonon frequency of 5.66 GHz was realized experimentally [2]. As for SPP, its wavelength can be shrank to much smaller than that of the lightwave at the same frequency by manipulating its general energy-bands, namely its dispersion curve. We observed and verified a novel effect, so called two-surface-plasmon-absorption (TSPA), which makes it possible to combine both wavelength-compression effect of SPP and threshold effect of the two-photon-absorption (TPA). By utilizing TSPA, diffraction-limit-overcoming photolithography was demonstrated with record resolution of ~1/11 of the exposure wavelength [3].

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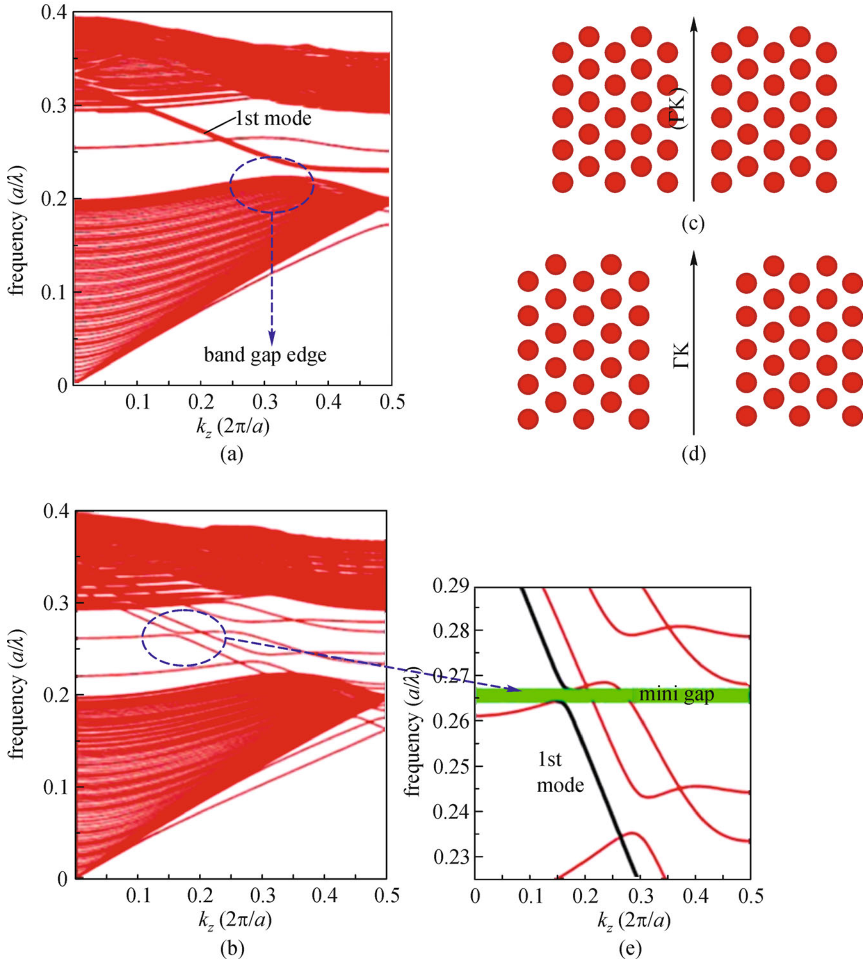
2 Photonic crystal waveguide

Photonic crystals provide an excellent example of manipulating general energy-bands of photon, namely the photonic energy-bands, in an artificial nanostructure [4,5]. Figures 1(a) and 1(b) show the simulation results of the photonic energy-bands for PCWG with different structures of W1 and W3 PCWG, which are formed by taking one or three rows of the holes away from the triangular lattice of photonic crystal, as shown in Figs. 1 (c) and 1(d), respectively. The periods of the photonic crystal were selected as *a* = 360 nm for W1 PCWG and *a* = 410 nm for W3 PCWG. It can be seen that, guide band and forbidden band (band-gap) are formed due to the periodic structure, and several defect modes appear within the band-gap. Entirely different photonic energy- bands for W1 and W3 PCWG indicate that photonic energy-bands can be manipulated simply by adjusting the width of the PCWG [6].

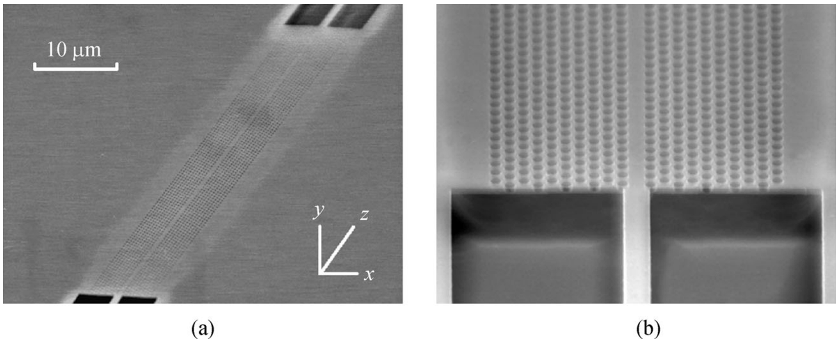
Let us focus the band-gap-edge of the photonic energy-band of W1 PCWG, where the slop of the dispersion curve of the defect mode is very small, which results in a very low group velocity, namely slow light effect can be obtained around this wavelength region. Figures 2 and 3 show our fabricated W1 PCWG with an air-bridge structure and the measurement results, respectively. For a W1 PCWG with 50.4 μm long, slow light effect was observed successfully with the group velocity slower than *c*/80 [7].

Figure 4 gives another example of manipulating the photonic energy band by nanostructure. Here, double slots are introduced into W3 PCWG, as shown in Fig. 4(a). It should be noticed that from Fig. 1(e), a MSB appears in the photonic energy-band of W3 PCWG, which comes from the coupling between the defect modes within the band-gap. Such a very narrow band-gap could result in a very sharp dip in the transmission spectrum of the W3 PCWG, but not being observed. The reason can be explained by Fig. 4(b), where the photonic energy band diagram of W3 PCWG shows that the MSB formed by the coupling between the fundamental mode and 4th mode is above the air light line and has huge vertical radiation loss. While the MSB below the light line is caused by the coupling between the fundamental mode and the band-edge mode,



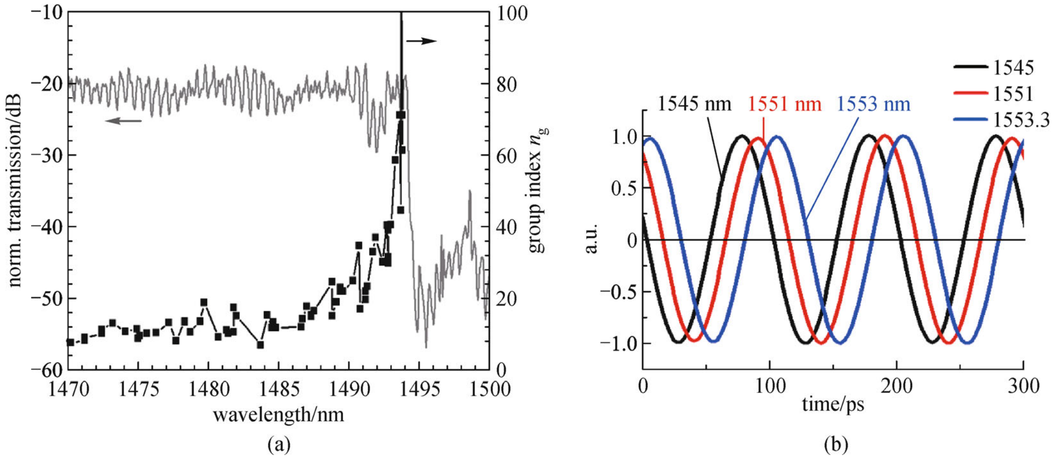
(a) (c) (d) (b) (e)

Fig. 1 (a) Photonic energy-band structure of W1 PCWG; (b) photonic energy-band structure of W3 PCWG; (c) schematic of W1 PCWG; (d) schematic of W3 PCWG; (e) MSB (mini-gap) in photonic energy-band structure of W3 PCWG [6]



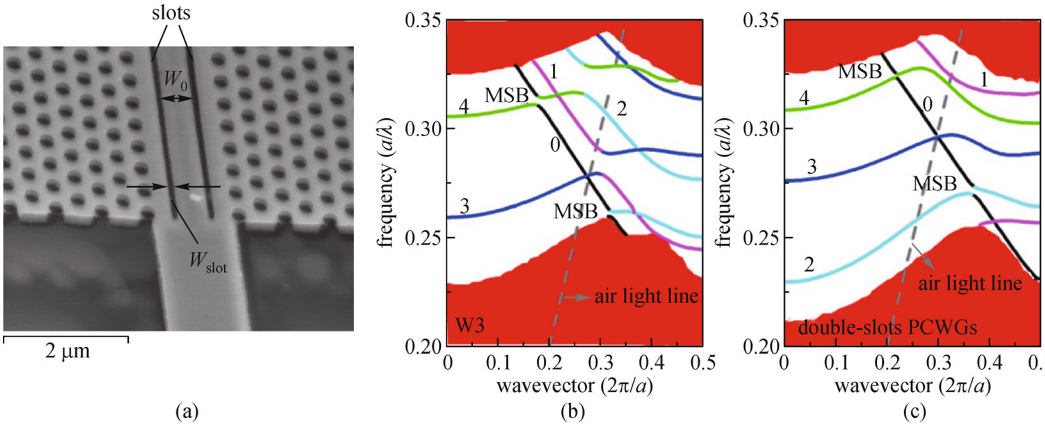
(a) (b)

Fig. 2 High quality W1 PCWG with air-bridge structure fabricated on silicon on insulator (SOI) substrate, where the period $a = 420$ nm, radius $r = 124$ nm, and the thickness of the silicon layer $h = 200$ nm. (a) is the total view and (b) is the view at the joint facet of the strip waveguide and the W1 PCWG [7]



(a) (b)

Fig. 3 (a) Measured transmission spectrum and group index of W1 PCWG with length of 480 μm. The gray line is transmission spectrum, black line with square symbol is group index [7]; (b) 10G microwave signal was delayed by the slow light effect at different wavelength. The time delay of 25 ps was obtained corresponding the group velocity is about $c/15$



(a) (b) (c)

Fig. 4 (a) Scanning electron microscope (SEM) image of the fabricated double-slots PCWG; (b) photonic energy-band for transverse electric (TE)-mode of W3 PCWG with $r/a = 0.28$; (c) photonic energy-band for TE-mode of double-slots PCWG with $r/a = 0.28$, $W_0 = 1.2a$, and $W_{\mathrm{slot}} = 0.2a$ [8]

which has larger transmission loss than that of the defect mode. Additionally, there are many modes coupling each other in W3 PCWG, such as 1st and 3rd modes or 2nd and 4th modes, which degrades the transmission performance of W3 PCWG.

The photonic energy-band is quite different when the double slots are introduced in Ref. [8]. Figure 4(c) shows that the MSB formed by coupling between the fundamental mode and the 2nd order mode lies below the air light line in the double slots PCWG, which can be guided better than that in W3 PCWG because of the less loss. On the other hand, the defect modes in the band-gap of the double-slots PCWG are effectively adjusted and the defect modes around the frequency of MSB are removed, which is beneficial to its transmission performance. In addition, two slots weak the coupling between the fundamental mode and the 2nd order mode. This is promising to obtain a narrow MSB, as well as a narrow dip in transmission spectrum. It was demonstrated experimentally a sharp and deep dip (22 dB with bandwidth of 6 nm) caused by MSB in the double-slots PCWG, which is 15 dB deeper than that in the W3 PCWG, as shown in Fig. 5 [8].

The photonic energy bands can be manipulated not only by the nanostructure, but also by external tuning. Figure 6 shows a W2 PCWG with an integrated titanium/aluminum microheater on its surface. Figure 7(a) shows the photonic energy-bands of the W2 PCWG. It can be seen that a MSB appears near the central wavelength of the band-gap. When the effective index of the W2 PCWG changes as the temperature under different heating power, the photonic energy-band is manipulated and the position of the MBS is moved, which results in shifting of the transmission-dip, as shown in Fig. 7(b) [1].

Based on this transmission-dip shifting, broadband switching functionality was observed in W2 PCW. The extinction ratio under different heating power is shown in Fig. 7(c). It can be seen that switching functionality with bandwidth up to 24 nm was achieved with an ultra-compact footprint of only 8 μm × 17.6 μm [1].

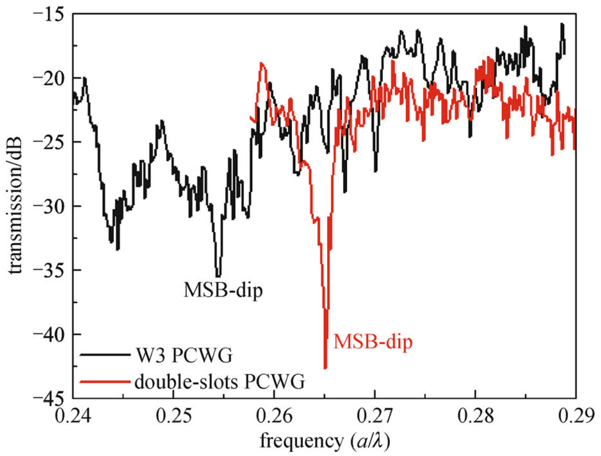
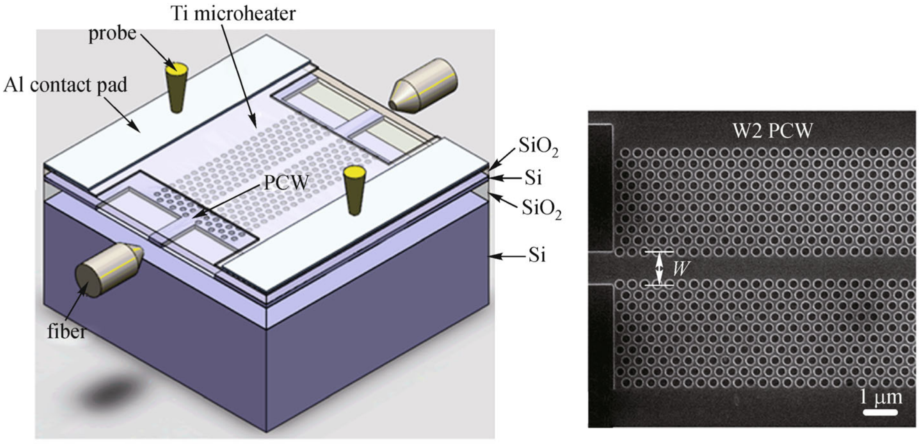


Fig. 5 Transmission spectra of W3 and double-slots PCWGs shown in Fig. 4 with a length of 50 lattice constants ($L = 50a$) [8]

3 Optomechanical crystal

Nanostructure can manipulate the energy-band for not only photons but also phonons, which provides an approach to develop new functional devices. Nanobeam structure, a kind of typical one dimensional optomechanical crystal [9], can manipulate general energy-bands of both photons and photons simultaneously. That is owing to the similar wavelength between photon and phonon in dielectric even though their frequency and group velocity are far different from each other. The nature of phonon is mechanical motion. Nanobeam structure has ability to control the interaction between light and mechanical motion through confining them spatial overlap and matching the difference



(a)

(b)

Fig. 6 (a) A W2 PCWG with an integrated titanium/aluminum microheater on its surface; (b) SEM image of the W2 PCWG [1]

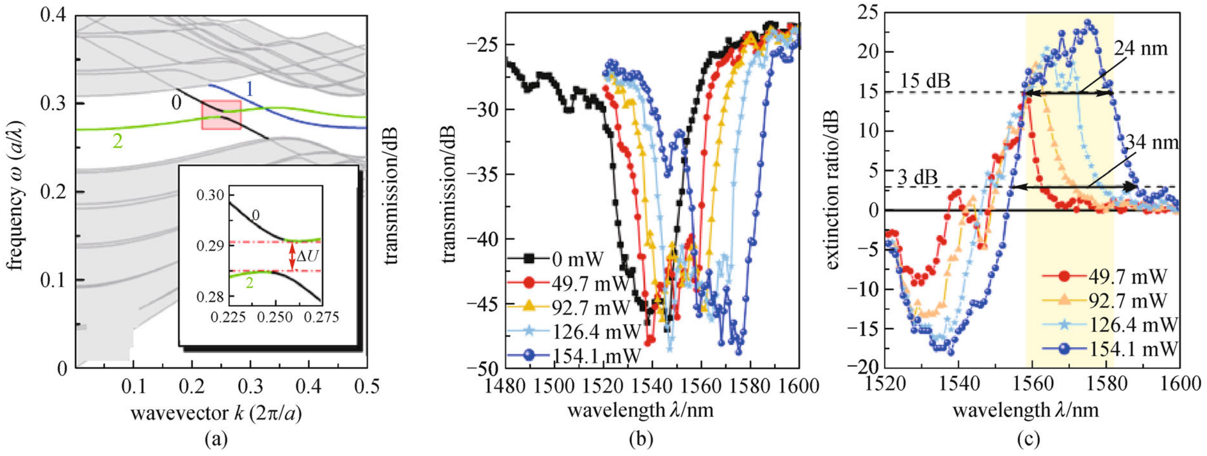
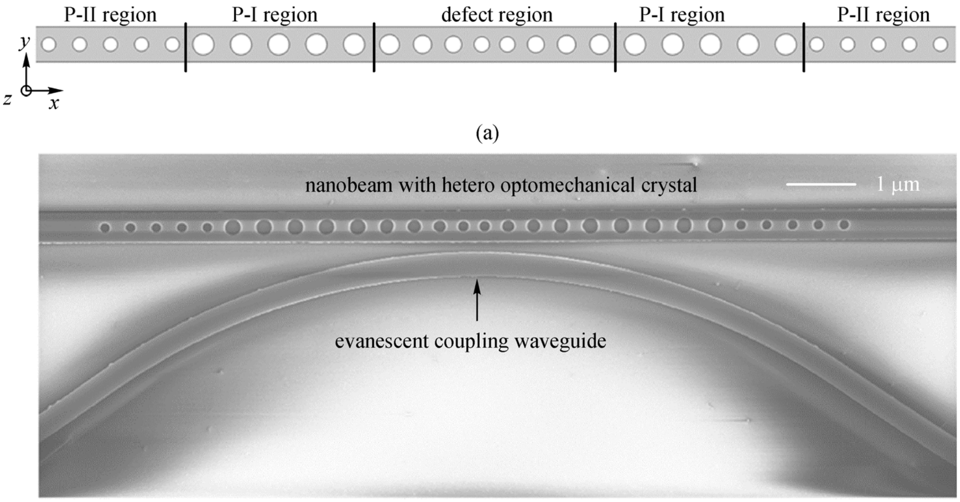


Fig. 7 (a) Photonic energy band of the W2 PCWG; (b) transmission spectra of the W2 PCWG under different heating power of the microheater; (c) extinction ratio of the W2 PCWG operating as an optical switch [1]

of their frequency to the cavity-resonance frequency. All of these can be characterized by frequency of the mechanical mode, optomechanical coupling rate, motion mass, and so on, and depends on the energy-band structure of photon and phonon in the nanobeam cavity. Therefore, engineering their energy-bands by designing the nanobeam properly is very crucial.

Conventional nanobeam based optomechanical crystal usually has uniform periodic structure and acts on both optical and mechanical modes by the same periodic structure, where designing energy-bands for photon and phonon is mutual dependent. It is very difficult to optimize them simultaneously. For example, the periodic structure selected to get high frequency of phonon band-gap tends not to provide the photon band-gap. To break these constrains, a nanobeam cavity based on hetero optomechanical crystals, which possesses two types of periodic structure, was proposed [2]. Figure 8(a) shows the schematic of proposed hetero optomechanical crystals and Fig. 8(b) shows the SEM image of the fabricated sample. Here an evanescent coupling waveguide was designed [10].

With optical and mechanical modes separately confined by two types of periodic structures, the energy-band of photon and phonon can be optimized independently, namely mechanical mode can be designed without the constraint of considering optical mode. Figure 9 shows the simulation results of the energy-bands for both photon and phonon. It can be seen that, the periodic structures of P-I and P-II act on the photon and phonon, respectively. Therefore, we can get a very high frequency of the mechanical defect mode by P-II while ensure a suitable frequency of photon band-gap with P-I. A mechanical frequency as high as 5.88 GHz can be obtained while the



(a)

(b)

Fig. 8 (a) Schematic of the one-dimensional hetero optomechanical crystal cavity; (b) SEM image of the top-view of the one dimensional hetero optomechanical crystal cavity with evanescent coupling waveguide after inductively coupled plasma (ICP) etching and electron beam (EB) removing process [10]

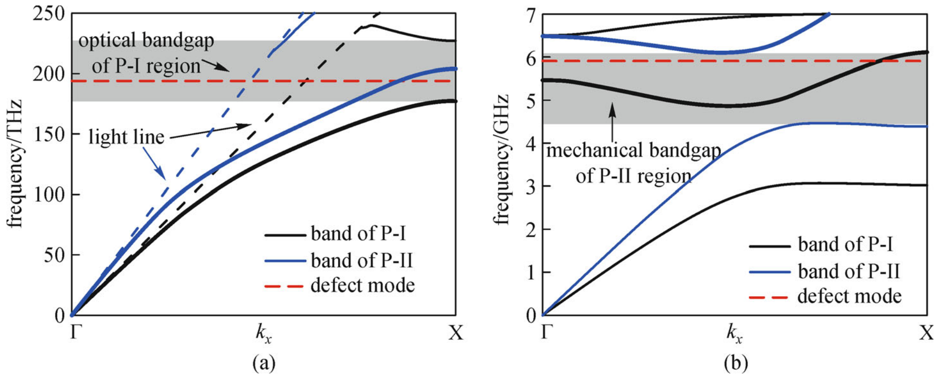


Fig. 9 (a) Energy-band for photon with light line. The gray region represents the optical band-gap formed by P-I periodic structure. The red dash-line represents a cavity optical mode with frequency of 194 THz; (b) *y*-, *z*-symmetric mechanical band (energy-band for phonon). The gray region represents the mechanical band-gap formed by P-II periodic structure. The red dash-line represents a mechanical defect mode with frequency of 5.88 GHz [2]

working wavelength of the optical cavity is settled at 1.55 μm. This will be the highest mechanical frequency reported in one-dimensional optomechanical crystal, to the best of our knowledge. Furthermore, due to the flexibility introduced by the hetero structure, the optical field and the strain field are concentrated inside the optomechanical cavity and resemble each other with an enhanced overlap. As a result, a record high optomechanical coupling rate of 1.31 MHz can also be estimated.

Figure 10 shows the measurement results of proposed nanobeam cavity [10]. Figure 10(a) is the transmission spectrum measured from the output of the evanescent coupling waveguide. The transmission dip at 1512.9 nm corresponds to the resonant optical mode of the nanobeam cavity. The power spectrum density of the mechanical signal is also presented in Fig. 10(b), which is measured by setting the wavelength of a tunable laser diode near the resonant wavelength of the resonant optical mode. The mechanical vibration of the cavity shows a high mechanical frequency peak of 5.66 GHz, which is the highest frequency demonstrated in one-dimensional optomechanical structure and in a good agreement with the theoretical one predicted by the energy-bands of phonon [2]. Due to the evanescent coupling waveguide, this structure can be directly used as functional components and integrated with other on-chip devices in future practical applications.

4 Surface plasmon polariton

Another exploration along the line of general energy-bands manipulation is our investigation of SPP [11,12]. SPP is a transverse magnetic surface electromagnetic excitation that propagates along the interface between a metal and a dielectric medium, a polariton formed through electron-photon coupling. The general energy-bands of SPP, namely the dispersion curve of SPP, is quite different from that of photons. By manipulating the general energy-bands of SPP, the wavelength of the SPP can be shrank to much smaller than that of the lightwave with the same frequency, which is capable of greatly compressing the light field or carrying the subwavelength information and shows the potential for diffraction-limit-overcoming photolithography. Here we observed and verified TSPA effect by carefully designing the experiment to exclude the possibility of TPA [3] and proposed TSPA based interference nanolithography (TSPA-IN) for large-scale subwavelength patterns.

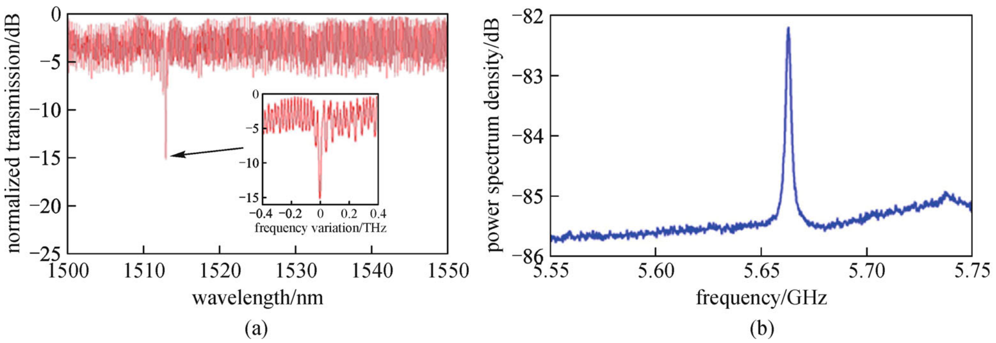


Fig. 10 (a) Normalized optical transmission spectrum of nanobeam cavity from the output of the evanescent coupling waveguide. The insert is the detail enlargement around the resonant frequency; (b) power spectrum density of the output optical signal [10]

According to the quantum optics, the SPPs can be quantized and treated as quantum in term of energy. Therefore, similar to TPA, the TSPA referring to a nonlinear effect could occur in the nonlinear medium near the metal surface, where two surface plasmons are absorbed to excite an electron state. As shown in Fig. 11, although the energy for the photon and SPP are identical for the same frequency, the larger wave vector of SPP, namely shorter wavelength of the SPP, can confine the space scale of this nonlinear process, which is what diffraction-limit-overcoming photolithography requests. Besides, the highly concentrated SPP field leads to the strong electromagnetic field enhancement at the metal-dielectric interface, which greatly promotes the occurrence of nonlinear absorption in the dielectric. Therefore, TSPA-IN makes it possible to combine both wavelength compressing effect of SPP and threshold effect of TPA. Furthermore, TSPA-IN provides an approach to solve the obstacles in conventional surface plasmon interference nanolithography, where the pattern linewidth depends on the period of plasmonic interference and is limited by pattern contrast. This is because TSPA-IN decouples the linewidth and the period by controlling the exposure power and SPP wavelength, respectively.

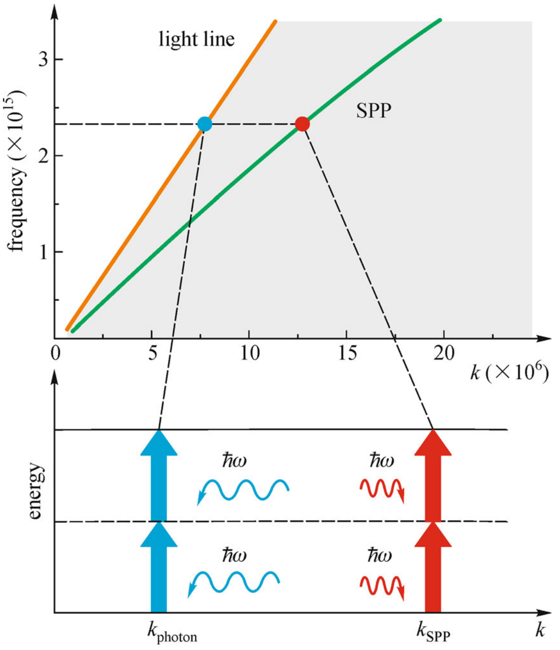


Fig. 11 Dispersion curve of light in vacuum (orange line) and SPP (green line), and the schematic mechanisms of TPA (blue) and TSPA (red) [3]

Figure 12 shows the experimental results of TSPA-IN. It can be seen from the surface profile of the resist pattern that, under the exposure wavelength of 800 nm, a diffraction-limit-overcoming photolithography was realized with the pitch of 240 nm. When average exposure power was reduced, a pattern with pitch of 70 nm was obtained, which corresponding to 1/11 of the exposure wavelength [3].

Also we can manipulate the energy-bands (dispersion curve) of the SPP with nanostructure to realize some new performances. As we know, bulk silicon cannot emit light efficiently due to its indirect band-gap. Nano porous silicon (NP-Si) [13] has been demonstrated to be with improved quantum efficiency because the quantum confinement effect breaks the space translational symmetry and relaxes the momentum conservation requirement. On the other hand, SPP has been effectively used to enhance the spontaneous emission from wide band-gap semiconductors like GaN/InGaN quantum wells and ZnO. Unfortunately this method is not so effective as far as the light emission from NP-Si is concerned because its central luminescent frequencies are much lower than the resonance frequency of the commonly used SPP waveguides. Aiming at improving the quantum efficiency from NP-Si, we proposed a nanostructure with a metal-rich Au $(1-\alpha)$-$SiO_2(\alpha)$ cermet waveguide to manipulate the energy-bands and engineer its resonance frequency to match the central luminescent frequencies of NP-Si [14].

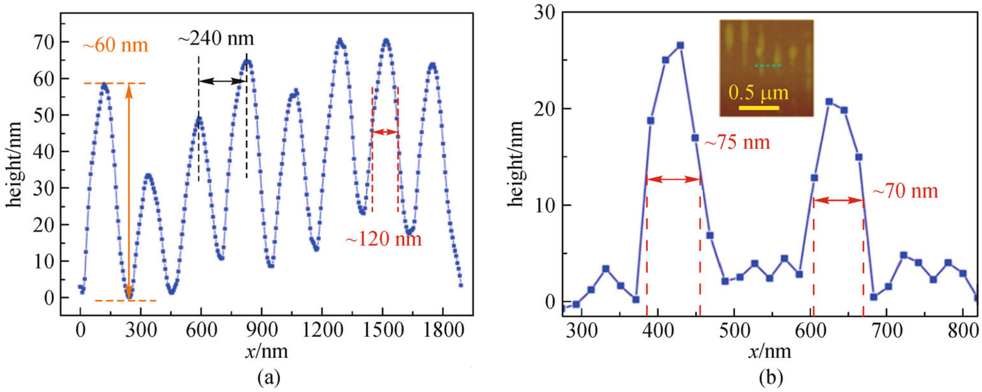
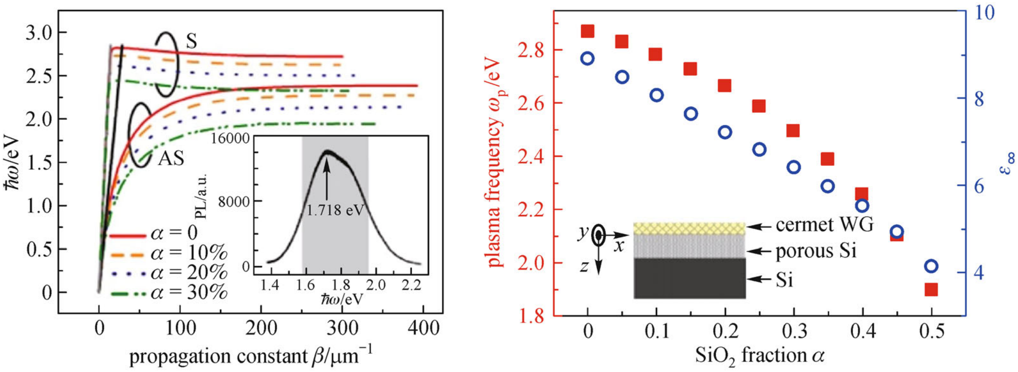


Fig. 12 Experimental results of TSPA-IN under the exposure wavelength of 800 nm. (a) Surface profile of the resist pattern at average exposure power of 630 mW for 10 s; (b) surface profile of the resist pattern at average exposure power of 230 mW for 15 s. The insect is the atomic force microscope (AFM) photo of the resist pattern [3]



(a) (b)

Fig. 13 (a) Dispersion curves of the Au($1-\alpha$)-SiO$_2$(α) cermet waveguide with different components $\alpha = 0$, 10%, 20%, and 30%. Inset is a typical photoluminescence spectrum of the NP-Si. The shaded area corresponds to frequency domain between two half maxima; (b) dependence on SiO$_2$ volume fraction α of resonance frequency ω_p (square) of the waveguide and high frequency dielectric constant ε_∞(circle) in Drude model of the metal-rich cermet. Inset is the schematic structure of a NP-Si layer with an Au ($1-\alpha$)-SiO$_2$(α) cermet waveguide [14]

Figure 13 shows the simulation results of the dispersion curves of the Au($1-\alpha$)-SiO$_2$(α) cermet waveguide with different components $\alpha = 0$, 10%, 20%, and 30%. A typical photoluminescence spectrum of the NP-Si is shown in the insert. It can be seen that the dispersion curve can be manipulated effectively by changing the components of the cermet. With increasing SiO$_2$, the resonance frequency of SPP can be reduced into the photoluminescence-frequency region of the NP-Si. The calculation results show that, by using this kind of the cermet waveguide, spontaneous emission rate inside a NP-Si layer can be enhanced so that the radiative recombination dominates. It is estimated that the internal quantum efficiency can be enhanced to over 80% [14].

5 Conclusions

This paper makes it clear that one of the essences of novel optoelectronic characteristics in nanostructures lies in the ability to manipulate the energy-momentum relations, which is defined as "general energy-bands" for a series of fundamental particles and their associated quasi-particles. The examples for engineering general energy-bands of photon, phonon, and SPP and realizing some new optoelectronic functions were given. Such as the ultra-compact footprint (8 μm × 17.6 μm) optical switch based on the photonic crystal slow light waveguide with a record wide bandwidth of 24 nm, nanobeam cavity with hetero optomechanical crystal with high phonon frequency of 5.66 GHz, and demonstrating and utilizing TSPA to achieve the diffraction-limit-overcoming photolithography with record resolution of ~1/11 of the exposure wavelength, and so on. It is important to go beyond individual devices and search for a more general rule behind each device and phenomenon for designing new functional devices on nanoscales.

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