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Design of high-Q silicon-polymer hybrid photonic crystal nanobeam microcavities for low-power and ultrafast all-optical switching

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Abstract

Owing to the unique optical properties high-Q photonic crystal nanobeam microcavities have been demonstrated in a variety of materials. In this paper the design of high-Q silicon-polymer hybrid photonic crystal nanobeam microcavities is investigated using the three-dimensional plane-wave expansion method and finite-difference time-domain method. We first discuss the design of high-Q nanobeam microcavities in silicon-on-insulator, after which the polymer is introduced into the air void to form the hybrid structures. Quality factor as high as 1×10^4 has been obtained for our silicon-polymer hybrid nanobeam microcavities without exhaustive parameter examination. In addition the field distribution of resonant mode can be tuned to largely overlap with polymer materials. Because of the overwhelmingly large Kerr nonlinearity of polymer over silicon, the application in all-optical switching is presented by studying the shift of the resonant frequency on the change of refractive index of polymer. The minimum switching intensity of only 0.37 GW/cm^2 is extracted for our high-Q hybrid microcavities and the corresponding single pulse energy is also discussed according to the pumping methods. The total switching time is expected to be restricted by the photon lifetime in cavity due to the ultrafast response speed of polymer. Our silicon-polymer hybrid nanobeam microcavities show great promise in constructing small-sized all-optical devices or circuits with advantages of possessing low-power and ultrafast speed simultaneously.

Keywords: Photonic crystal cavity; All-optical switching; Silicon-polymer hybrid

1. Introduction

Since numerous theoretical results indicate that ultrahigh-Q microcavities can be realized by adopting only one-dimensional (1D) periodicity, photonic crystal nanobeam microcavities (PCNMs) have been intensively and extensively investigated in various materials such as semiconductor, polymer, silicon dioxide and even single-crystal diamond [1–8]. Owing to the unique optical properties such as small footprint, ease of design and fabrication, PCNMs with direct coupling between waveguide and cavity have been used to construct low-threshold laser, sensitive sensor, all-optical switch and modulator [9–12]. In addition PCNMs have been found as an excellent platform to study the optomechanical

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effect [13–15]. Previously most of the PCNMs are fabricated in semiconductor materials, silicon for example, because the fabrication method is compatible with the modern microelectronic integrated circuit technology. So PCNMs based on semiconductor materials show unprecedented advantages in building integrated and small-sized all-optical switches. Recently all-optical switching with pico- or femtojoule switching energy has been demonstrated in silicon-on-insulator (SOI) PCNMs [11,12]. Extremely low power optical bistability has also been reported in silicon 1D PC nanocavity [16]. However, the total switching time is hundreds of picoseconds or nanoseconds, due to the recombination time of free carriers generated in semiconductor materials. Despite various sophisticated manipulations such as ion implantation, placement of reverse bias, and using ultrasmall nanocavities, the total switching time is still restricted in the picosecond or nanosecond range [17–19].

It is argued that the strong optical nonlinearity in semiconductor is mainly caused by the generation of free carriers, which is responsible for the slow switching behavior. One feasible solution to solve the problem is to avoid using the nonlinearity in semiconductor materials for all-optical switching. Quite recently *Maksymov* introduces the concept of hybrid plasmonic-photonic crystal nanobeam cavities for achieving optical switching and logic gates, where a cylindrical plasmonic nanoantenna is placed on the top surface of a SOI PCNM to modify the transmission of resonant frequency [20]. Another hybrid structure is proposed by *Schriever* as a locally infiltrated slot PCNM, where the electric field of the resonant frequency is largely overlapped with the infiltrated nonlinear materials [21]. Nevertheless, the fabrication method for the above mentioned hybrid PCNMs seems stringent, which requires precisely positioning the metal nanoparticle or locally infiltrating the slot region. Moreover, studies on the switching time are still scarcely discussed for the above hybrid structures.

Our previous investigations reveal that polymer possesses excellent Kerr nonlinearity, which is well suited for achieving ultrafast all-optical switching [22]. Lately we have successfully fabricated high-quality semiconductor-polymer compound nonlinear PC slabs based on the nanoimprint lithography technique [23,24]. They are such kind of compound structures where organic polymer materials are infiltrated completely into the void region of two-dimensional (2D) semiconductor PC slabs. At the same time we have also theoretically investigated the dynamics of all-optical switching in a 1D semiconductor-polymer hybrid nonlinear PC [25]. The conclusion is drawn that under the pumping of femtosecond pulse the introduction of highly nonlinear polymer material with femtosecond relaxation time can realize all-optical switching in the femtosecond range in spite of the slow response speed of the semiconductor material. The physical origin is attributed to the overwhelmingly large Kerr nonlinearity and ultrafast relaxation time of polymer. Although semiconductor-polymer hybrid planar PC structures have been investigated previously [26,27], almost all the design schemes are based on the 2D patterns, where the size of the devices is relatively large. Moreover, the ways on how to achieve low-power and ultrafast integrated all-optical switching for those hybrid structures have not been sufficiently discussed [28]. On that consideration we put forward the concept of silicon-polymer (Si-polymer) hybrid PCNMs, where the device sizes can be greatly reduced and also possess excellent Kerr nonlinearity.

According to the fabrication procedure in [24], it can be envisaged that our Si-polymer hybrid PCNMs can be fabricated as follows. The nanobeam microcavity pattern is first sculpted onto the top Si layer of the SOI structure by using the e-beam lithography and reactive ion etching. Then polymer is uniformly infiltrated into the air void region of the nanobeam structure utilizing the nanoimprint lithography technique. In this case not only the air holes but also the top and two side surfaces of Si nanobeam are entirely covered with polymer. Hence specific design strategy for realizing high quality factor is needed for our Si-polymer hybrid PCNMs. In our previous paper we design a high-Q double-heterostructure PCNM in low-refractive-index material, where mechanism of slow group velocity at the band edge to enhance the quality factor is implemented [29,30]. As is well known that delicate taper segment between the cavity and mirror, which is to avoid abrupt termination and reduce the scattering loss, is widely chosen for the design of high-Q PCNMs. Such a cavity configuration is of high efficiency especially for high-refractive-index materials, semiconductor for example [3,4,31]. However, this inevitably requires strict nanofabrication precision, which will make the structure vulnerable to fabrication imperfection. Therefore it is meaningful to examine whether it is possible to extend our double-heterostructure scheme from low-refractive-index case to high-refractive-index hybrid structure.

In this paper, we present the design of high-Q Si-polymer hybrid PCNMs based on the double-heterostructure configuration. Without exhaustive parameter examination, quality factor as high as 1×10^4 is