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Nanofabrication of optical structures and devices for photonics and biophotonics

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Abstract. Nanofabrication offers promise for the design of artificial materials with optical properties unlike those of materials occurring in nature and for the design of new and exotic optical devices. We describe some specific ideas for applications in this area, and present some laboratory results on the development of these applications.

1. Introduction

Recent advances in the technology of nanofabrication offer the possibility of manufacturing new optical materials and devices with unprecedented control. One possible application is the creation of new materials with optical properties entirely unlike those of materials occurring in nature [1–7]. Such materials could, for instance, possess group refractive indices, group velocity dispersion, and optical nonlinearities very much larger than those of conventional materials.

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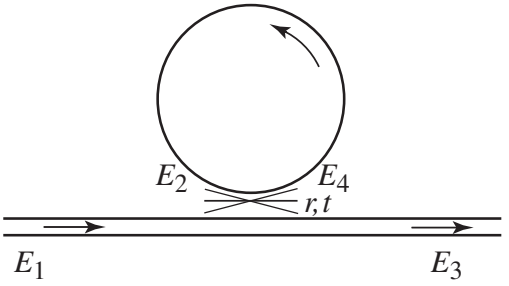

Figure 1. Optical disc resonator coupled to an optical waveguide.

Nanofabrication can also be used to manufacture new optical devices such as optical switches [8, 9] and photonic sensors including biosensors [10]. The present article describes some ideas along these lines and describes the progress of our research program toward achieving these goals.

The basic approach we have taken is to fabricate devices based on the building block of a disk or ring resonator coupled to an optical waveguide. This structure is illustrated in figure 1. If the frequency of the incident light is tuned to a resonance frequency of the optical resonator, the intensity I_2 of the light circulating within the resonator can be much greater than the incident intensity I_1. The ratio of these two quantities is the buildup factor $B = I_2/I_1$. One can readily show [3] that, for the case considered here in which internal loss is negligible and in which the field is tuned to exact resonance, the buildup factor is given by

$$B = \frac{1+r}{1-r}, \tag{1}$$

where r is the amplitude reflection coefficient describing the optical resonator. Because of the buildup of light intensity, such a device displays an enhanced nonlinear optical response. The strength of this response can be shown [11] to scale as the square of the buildup factor B. By detuning the optical frequency slightly from the resonance frequency, the phase shift experienced by the light in interacting with the resonator can be accurately controlled. This phase shift is readily shown to be given by the expression [11]

$$\Phi = \pi + \phi + 2\arctan\frac{r\sin\phi}{1-r\cos\phi} \tag{2}$$

where $\phi = (\omega - \omega_R)T$ can be thought of either as the single-pass phase shift or as the normalized detuning of the optical frequency ω from the resonance frequency ω_R. Here T is the transit time of light in travelling once about the resonator and is given by $T = 2/c$, where R is the radius of the disk or ring, n is the refractive index of the disk or ring material, and c is the speed of light in vacuum.

Two examples of devices that make use of optical resonators are illustrated in figure 2. Figure 2(a) shows a waveguide-based Mach–Zehnder interferometer with a disc resonator coupled to one arm. Light passing through this arm thus experiences a much larger phase shift than light passing through the other arm. Light can thus be routed to either of the output ports depending on the relative intensities of the two input signals. The switching speed of such a device is limited by the ring-down time of the optical resonator. This response time will be of the

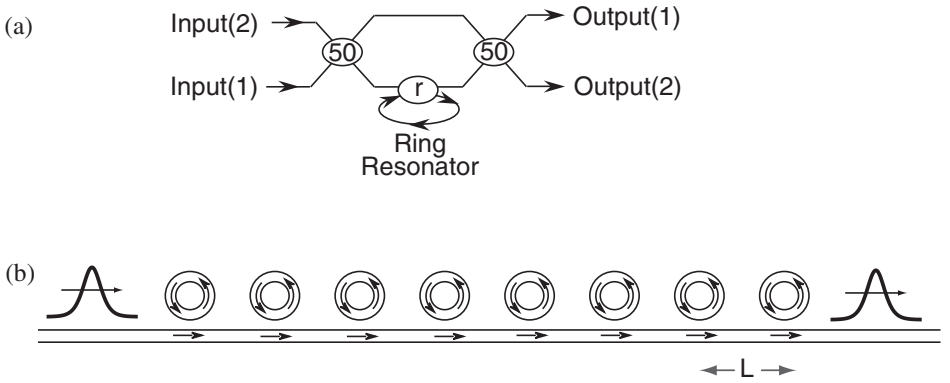

Figure 2. Two photonic devices that make use of the properties of disc or ring resonators. (a) Mach–Zehnder interferometer containing a ring resonator in one of its arms. Due to the enhancement of the nonlinear response of the arm containing the ring resonator, this device displays low switching energies. (b) A side-coupled integrated spaced sequence of resonators (SCISSOR) is shown. This device can serve as a controllable optical delay line and provides large controllable nonlinearity and dispersion.

order of $\tau = BT$. Note that since the response time scales as B, whereas the nonlinear phase shift scales as B^2, by choosing R to be small and B to be large a device can be fabricated which is both fast and highly nonlinear.

Another example is shown in part (b) of figure 2. It consists of an optical waveguide coupled to a series of optical resonators. The resonators can be of arbitrary design, although in our experimental work we are concentrating on resonators in the form of a ring waveguide or a whispering gallery mode [12, 13] of a disc. A pulse of light is shown propagating through this structure. Evanescent coupling between the waveguide and resonator injects light into each resonator where it circulates B times before being coupled back into the waveguide. For a densely packed collection of resonators, a light wave spends much more time circulating within each resonator than in propagating between resonators. Thus the group velocity of propagation can become very small [3]. Since the time delay acquired in interacting with each resonator depends critically on the detuning of the optical wave from the resonance frequency, this device displays tailorable dispersion with a size that is many order of magnitude larger than that of conventional materials. Also, because of the build-up of intensity within each resonator, the nonlinear response of this structure is greatly enhanced. Under appropriate conditions, these dispersive and nonlinear effects can precisely balance one another, leading to the propagation of optical solitary waves [4].

2. Fabrication of nanophotonic devices

As mentioned above, the standard building block of our photonic devices is an optical resonator coupled through evanescent fields to an optical waveguide. The details of a typical design are shown in figure 3. Such designs have successfully been fabricated previously [14]. Both a side view (upper part of figure) and top view (lower part) are shown. The waveguiding structure is grown by molecular beam epitaxy at the University of Rochester. The waveguiding region is composed

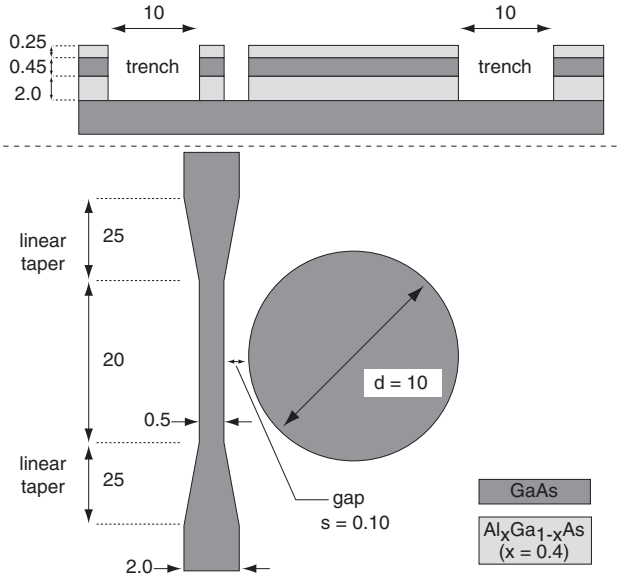

Figure 3. Design of the basic disc resonator structure.

of GaAs and is clad above and below by AlGaAs. The disc resonator is approximately 10 μm in diameter and is separated from the waveguide by a thin air gap. We fabricate devices with a variety of gap thicknesses in order to control the degree of coupling to the resonator. Note that the waveguide is tapered at the ends to facilitate the coupling of light into the guide. The horizontal patterning is performed at the Cornell Nano-Scale Science and Technology Facility using state-of-the-art nanofabrication procedures. We have experimented with several procedures, although most of our work is performed using the procedure shown schematically in figure 4. The final etch (step 7) is performed using electron cyclotron resonance etching (ECR). One of our finished structures is illustrated in figure 5, which shows a ring resonator coupled to an optical waveguide. This device was fabricated using the procedure of figure 4 with the final etch performed using electron cyclotron resonance. Note the smoothness of the sidewalls of the structure. We are presently in the process of characterizing the optical properties of the devices we have fabricated.

3. Development of a photonic biosensor

There is great need for robust, sensitive devices that can detect biological agents and especially of biological pathogens [15]. Photonic techniques offer significant possibilities for the development of such devices. One procedure is to make use of spectroscopic techniques for the precise spectrochemical analysis of the chemical species that are present in the biological material [16]. Indeed, some of the most sensitive biosensors [17] proposed to date make use of such spectroscopic methods. Another approach is to allow the biological material to fall onto a sensor element, the properties of which are then detected optically. The use of surface plasmon resonance has been exploited for the development of sensitive devices of this sort [18–20].

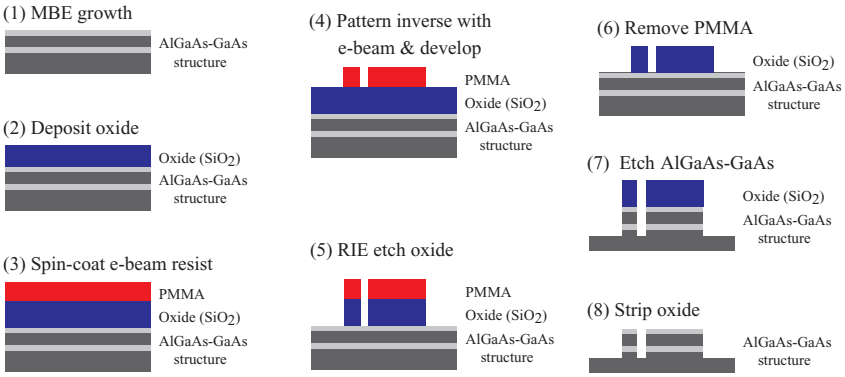

Figure 4. Fabrication procedure used in the manufacture of the photonic devices. MBE = molecular beam epitaxy, CAIBE = chemically assisted ion beam etch, PMMA = poly methyl methacrylate.

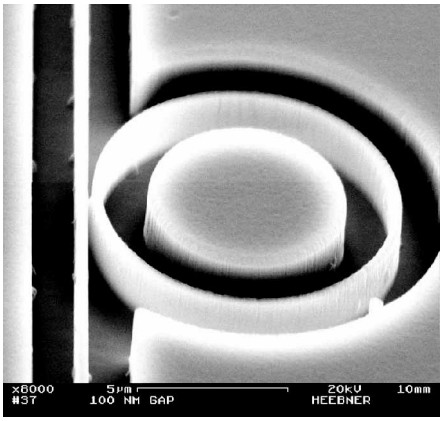

Figure 5. Example of a ring resonator fabricated in GaAs.

We are developing a sensitive photonic biosensor based on the use of disc resonators. The operation of the biosensor being developed [21] is illustrated in figure 6. Both panels show fine-difference time-domain numerical simulations of the intensity distribution in a region including the disc and waveguide. The panel on the left shows the device in the absence of an absorbing particle, and it is seen that the intensity of the light within the resonator is much larger than that of the incident light beam, and that the transmission through the waveguide is essentially 100%. The panel on the right shows how the field distribution is changed when an absorbing particle falls onto the disc resonator. One sees that the circulating intensity is greatly reduced and that, because of a destructive interference between the two fields that contribute to the output, the transmitted intensity drops essentially to zero.

In order to allow for the detection of a specific biological pathogen or other biological substance, we are developing techniques for the specific binding of a particular substance onto the surface of the disc resonator. While the technique of

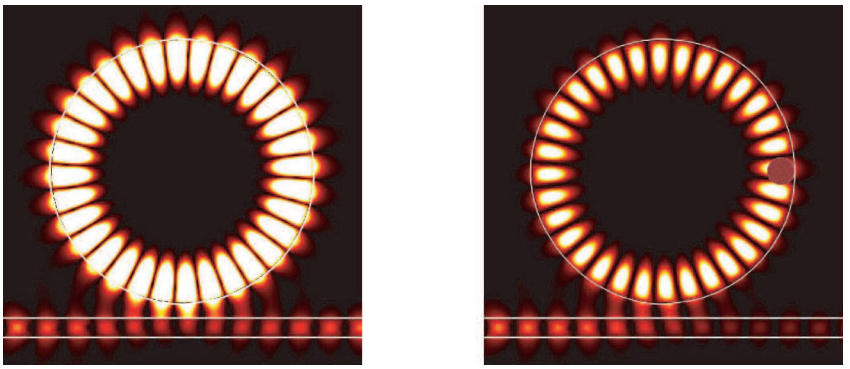

Figure 6. Conceptual design of a disc resonator photonic biosensor. The upper surface of the disc resonator is coated with a layer of binding material. When a pathogen falls onto this surface it is selectively bound to it, producing to an increased loss mechanism that leads to decreased transmission.

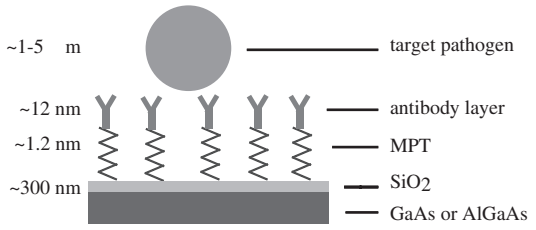

Figure 7. Laboratory procedure for selective binding of biological materials onto a GaAs or AlGaAs substrate.

specific binding onto glass surfaces is well established [22], the implementation of this technique for other photonic materials, such as GaAs, is still in its infancy. The procedure being developed for the specific binding onto GaAs is shown in figure 7. We first coat a very thin layer of SiO_2 onto the GaAs or AlGaAs substrate using plasma-enhanced chemical vapor deposition (PECVD). This layer must be thin enough for an evanescent optical field to penetrate, but thick enough for adhesion promoters to work properly. We then attach a thin layer of mercapto-propyl triethoxy silane (MPT) to the surface by dipping into a liquid solution. We finally attach an antibody layer that can provide selective binding to a specific pathogen.

We have succeeded in making this technique work for the case of a biotin-streptavidin system immobilized onto a thin glass layer deposited on top of a gallium arsenide photonic substrate. Our experiment involved three types of surfaces: GaAs wafers, GaAs onto which a sub-micron surface layer of silica had been deposited, and a glass microscope slide (as a control). These surfaces were cleaned in an oxygen plasma and were coated with a MPT silane layer using standard wet-chemistry techniques. A biotin layer was then deposited onto the silane layer and finally a layer of Cy3-tagged streptavidin was deposited. At all steps in this process the contact angle of a water droplet with the surface was monitored. These measurements indicate that all depositions adhered to the

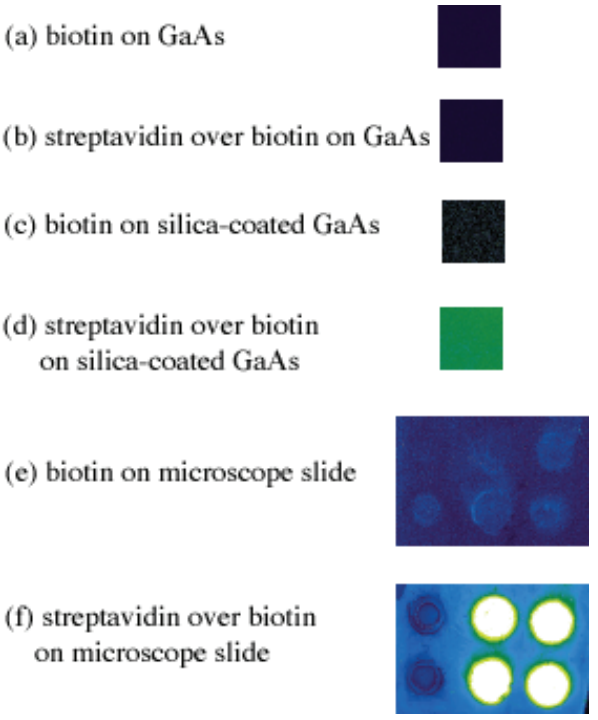

Figure 8. Laboratory demonstration showing selective binding of a biological material onto a GaAs substrate.

underlying surfaces. Some results are shown in figure 8. In all cases a false-colour image of the fluorescence from the surface is shown. Comparison of the first four photographs shows that we are able to selectively bind to a GaAs substrate if the substrate is first covered with a silicon oxide layer. In the bottom two photographs, for the column on the left no biotin was allowed to reach the surface and no fluorescence is observed, thus demonstrating the ability of selectively determine the presence of streptavidin.

4. Summary

In summary, we have described some ideas for the development of new materials and devices, including a photonic biosensor, that can be constructed using nanofabrication techniques. We have also presented preliminary results demonstrating the promise of these approaches.

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