Nano-photonics: Recent Advances

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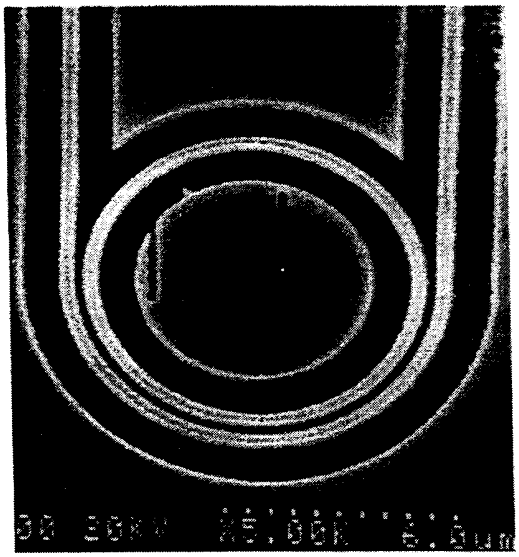
ABSTRACT

We have designed, fabricated and demonstrated ultra-compact directional couplers (< 30 μm) and "race-track" micro-resonators as nano-photonic building blocks for a range of WDM devices, including ultra-compact directional couplers, channel-dropping filters, 1 x *N* demultiplexers and 2 x 2 crossbar switches.

Keywords: Nano-photonics, resonators, switches, waveguides, semiconductors, integrated optics, WDM.

Nanophotonics is an emerging field in photonics. It is an enabling technology that allows us to fabricate photonic devices on a much smaller scale and to realize photonic integrated circuits with much higher device-count and functional density. An example of nanophotonic device is the micro-ring resonator which has been used as the basis for a new class of Wavelength Division Multiplexing (WDM) devices that offers potential advantages in performance, size and cost. Waveguide-coupled microcavity ring and disk resonators in AlGaAs/GaAs material system with high finesse (> 100) and 22-nm free-spectral range (FSR) have been demonstrated [1]. These devices have also been demonstrated in other material systems [2]. The large FSR of these resonators results from their extremely small size (~10 μm diameter), which is made possible by the use of waveguides with a large lateral index contrast of 3.4 to 1. Such dimensions would conceivably enable realization of large-scale photonic integrated circuits, such as an optical cross-connect switching fabric, demanded by future dense WDM systems. We believe this technology will be one of very few viable options for realizing future high-density photonic integrated circuits that will become more prevalent with the advent of dense WDM communication systems.



Photonic-Wire Laser Coupled to Nanoscale Waveguide

The emergence of nano-scale photonic devices is triggered by advances in nanofabrication technology as well as in our understanding of low-dimensional quantized photonic and electronic structures. Historically in our group, our interest in low-dimensional photonic structures arose from an attempt to minimize the laser threshold power by maximizing the photon capture efficiency into the desired lasing cavity mode. This quantity, known as the spontaneous emission coupling factor (β), has a value of 10^{-5} at threshold for conventional laser diodes. It turns out that this value can be increased to nearly 1 (the theoretical limit) by using strongly guided two-dimensional dielectric waveguides with cross sectional dimensions smaller than a quarter of an optical wavelength in the material. In that case it is found that spontaneous emissions emitted in a certain polarization and in certain directions are greatly suppressed, and almost all spontaneous emissions are effectively channeled spatially into a particular desired direction and spectrally into one cavity mode. An example of such a photonic structure is shown in Fig. 1. It consists of a ring-shaped semiconductor cylindrical waveguide forming a ring cavity, coupled evanescently to a U-shaped waveguide forming the output. The ring waveguide is bonded onto a glass substrate with a much lower refractive index. The waveguides have a cross section of only 0.2 µm x 0.2 µm. We call this a *photonic wire* laser as the optical confinement occurs strongly in both the transverse dimensions, in analogy to quantum wire which confines electrons in two directions. The total mode volume in the waveguide is only 0.3 cubic micrometer, making this one of the smallest lasers ever demonstrated.

Similarly, the photonic analog of quantum well would be a *photonic well*, which is simply a strongly guided waveguide with one of the transverse dimensions smaller than an optical wavelength. An example of such a waveguide that is useful for planar integrated circuits would be one that has strong lateral confinement (formed by a large index contrast) in the plane direction but the conventional layer structure of a weakly guided waveguide in the vertical direction. Because of the lateral confinement, this photonic well waveguide would be able to curve around sharply forming very compact cavities, bends, branches and crossovers, and, consequently, enabling integrated optic devices to be greatly miniaturized.

Fig. 2 shows a micro-ring resonator in GaAs/AlGaAs materials formed by the photonic well waveguide, coupled evanescently to two similar straight waveguides, across gaps of only 100 nm. The waveguides are formed by etching deep side trenches into the semiconductor using inductively coupled plasma reactive-ion etching (ICP-RIE). The patterns were defined by direct-write electron-beam lithography. ICP-RIE is a relatively new dry etching method and has not been widely utilized for etching of submicron structures. A principal advantage of ICP-RIE compared to conventional to RIE methods is the ability to independently control the ion energy and flux density. With ICP-RIE, we have achieved deeply etched nanometer-scale structures in GaAs/AlGaAs materials with aspect ratios as high as 30:1 and very smooth sidewalls with typical roughness less than 10 nm.

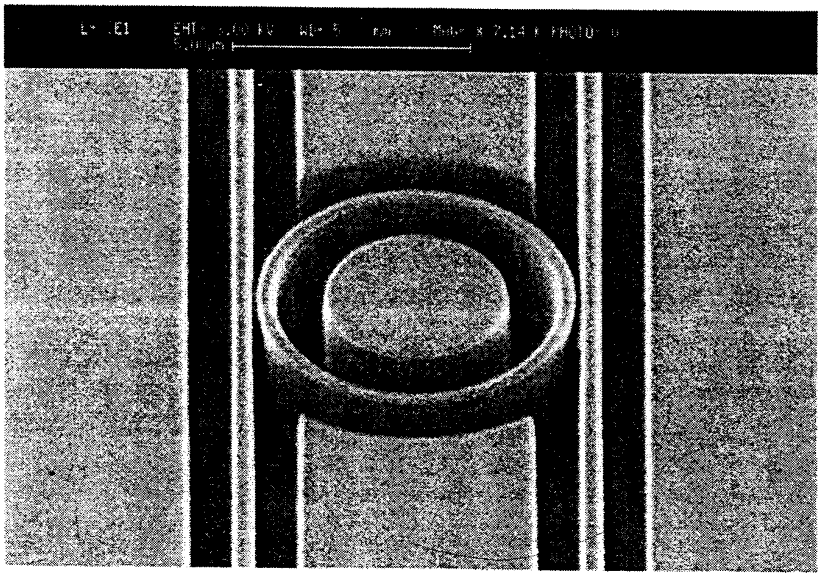


Fig. 2: A micro-ring resonator and two coupled waveguides. The diameter of the ring is 6 µm, the width of the waveguide is 0.4 µm, and the width of the gaps is 0.1 µm.

The conventional ring resonators are coupled to input and output waveguides via a "point contact", and therefore for sufficient coupling a very small gap of the order of 100 nm is required. As an alternative we and others have proposed a "race-track" resonator [3] which achieves the same desired coupling factor by trading off a longer coupling distance for a wider gap. We have found that as a result the fabrication is much more tolerant. Fig. 3 shows SEM pictures of a resonator-based channel dropping filter and the race-track resonator. Note that the waveguides are 0.4 µm wide but taper to 2 µm outside the resonator region for easier input coupling and to reduce optical loss.

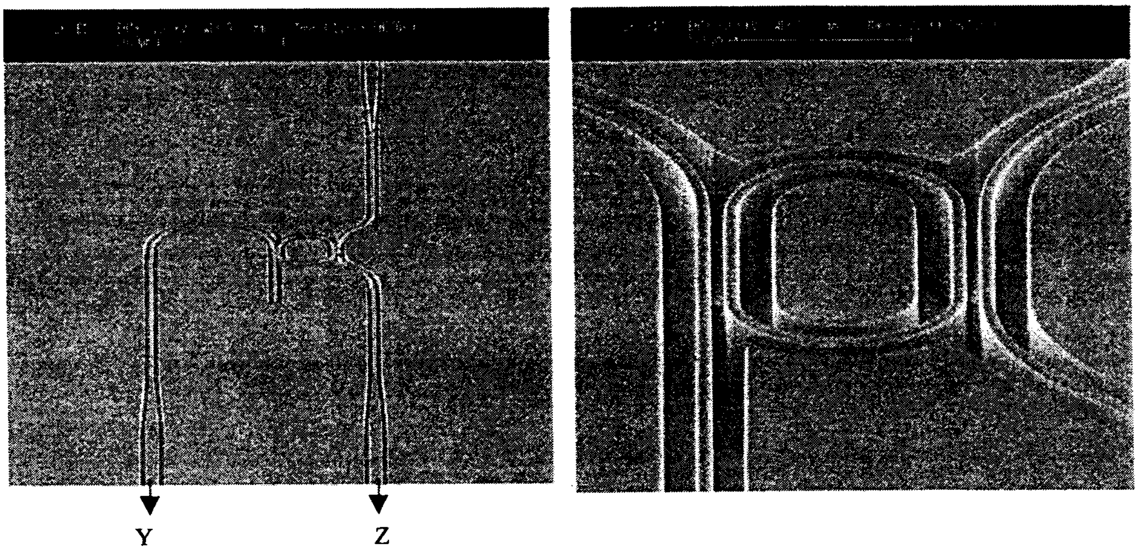


Fig. 3: (a) A race-track resonator coupled to two waveguides. (b) Close-up view of the race-track resonator.

The principle of operation which makes the microcavity resonator a versatile WDM device (a wavelength filter/switch, a multiplexer, even a modulator) is very simple, and is based on the concept of resonance. Essentially, the ring forms a Fabry-Perot interferometer with the two couplers forming the mirrors. The mirror reflectivities are determined by the coupling factors between the ring and the two coupled waveguides. The resonance wavelength (λ_m) is defined by the resonance condition: $l_{eff}n_{eff} = m\lambda_m$, where l_{eff} is the effective round trip length of the cavity, n_{eff} is the effective index of the waveguide, and m, an integer, is the order of the resonance. Hence, the free spectral range, defined as $\lambda_m - \lambda_{m+1}$, is large when the cavity length is small. In operation, input light (see Fig. 3a) will exit through port Y (called the reflection port) when the wavelength is off resonance, and exit through port Z (called the transmission port) when on resonance. Typical spectra from these ports for the race-track resonator device are shown in Fig. 4, where a switching efficiency of 80% was achieved. Resonance linewidth as small as 0.2 nm and cavity Q factors as high as 10,000 have also been obtained.

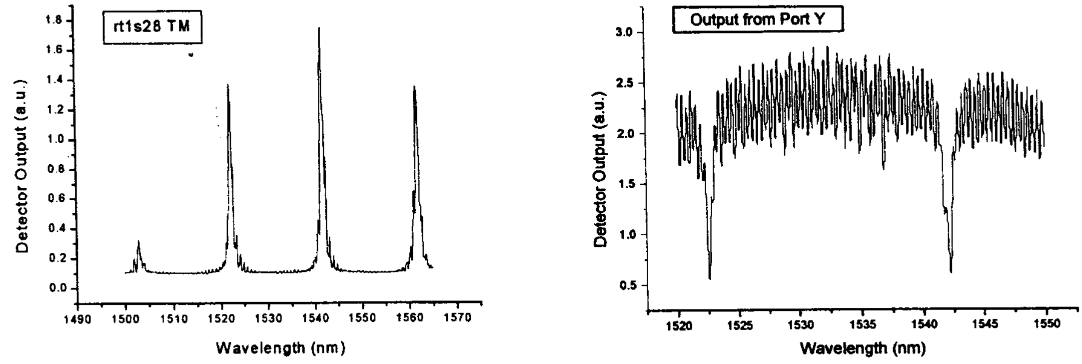


Fig. 4: (a) Reflection spectrum at output Y:
The oscillations are due to the Fresnel reflections.

b) Transmission spectrum at output Z.
Note the different wavelength range.

Using the race-track resonators as a building block, we have fabricated more sophisticated photonic integrated circuits such as 2 by 2 cross-bar switches and 1 by 8 and 1 by 16 wavelength multiplexer/demultiplexers. The SEM pictures of these devices are shown in Fig. 5. These devices illustrate the functional versatility and the size advantage of microcavity resonators. The *N* x *N* crossbar switch, for example, is a scalable add-drop matrix switch, an essential component for optical add-drop multiplexers (OADM) and optical cross-connects (OXC). The resonator-to-resonator spacing can be as small as 50 μm, which means that the size of an *N* x *N* OXC fabric may be no more than 50*N* x 50*N* μm^2. In principle, optically transparent OXC can be achieved by incorporating optical amplifiers in the circuit to compensate for the propagation loss.

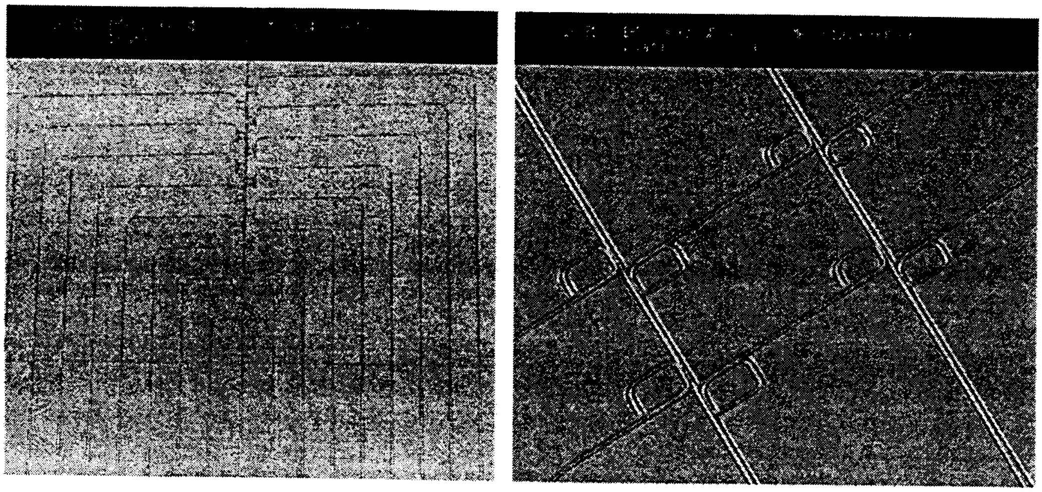


Fig. 5: (a) 1 x *N* (*N* = 16) demultiplexer, (b) 2 x 2 crossbar switches

In multi-resonator devices, the resonators are designed to be slightly different in length according to the targeted resonance wavelengths. In practice, the resonance wavelengths are very sensitive to any variation or deviation in the cavity length and may need to be actively controlled, for example, by electro-optic tuning.

High density integrated optics for WDM requires a wide array of ultra-compact devices, not just filters and multiplexers (wavelength-sensitive devices), but also couplers and switches (broadband devices), as well as the ubiquitous curved waveguides and crossovers. In fact, in conventional integrated optics, the level of integration is limited by the size of curved waveguides as well as the active device dimensions. On the other hand, curves in nanophotonic waveguides is not an issue as amply evident in the microring resonators. Couplers and switches based

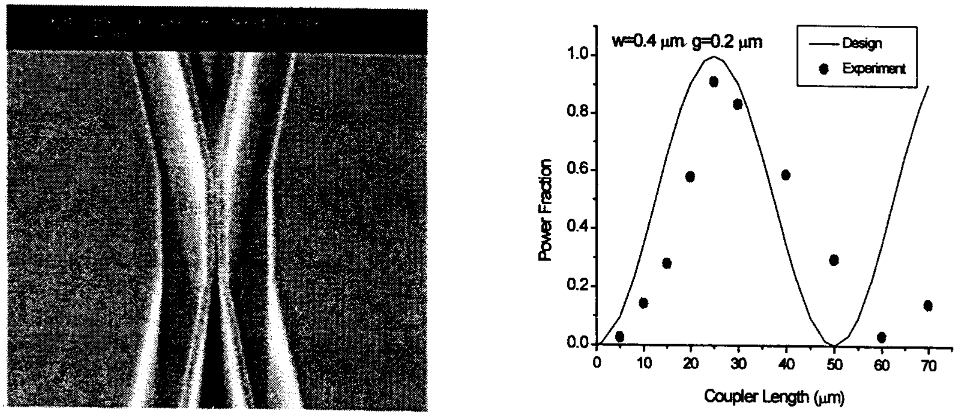


Fig. 6: (a) An SEM image of a coupler. (b) measured results of power coupling.

on nano-photonic waveguides can be significantly smaller than the conventional devices, not only in the coupling region but more significantly in the input and output sections where curved waveguides, such as S-bends, are used. A fabricated coupler with a length of only 3 μm and a gap size of 0.15 μm is shown in Fig. 6(a). Fig. 6(b) shows the measured power transfer for different coupler lengths in the case of $w = 0.4$ μm and $g = 0.2$ μm. Note that full power transfer occurs at L_c=25 μm, making this probably the shortest directional coupler ever demonstrated.

In conclusion, we have designed and demonstrated ultra-compact directional couplers and race-track micro-resonators as nano-photonic building blocks for a range of WDM devices, including channel-dropping filters, 1 X N demultiplexers and 2 x 2 crossbar switches.

References:

[1] D. Rafizadeh, J. P. Zhang, S. C. Hagness, A. Taflove, K. A. Stair, S. T. Ho, "Waveguide-coupled AlGaAs/GaAs microcavity ring and disk resonators with high finesse and 21.6-nm free spectral range", Optics Letts., vol. 22, pp. 1244-1246, 1997.

[2] B. E. Little, J. Foresi, H.A. Haus, E. P. Ippen, W. Greene, and S. T. Chu, "Ultra-copmact Si/SiO2 micro-ring resonator channel dropping filter," IEEE Photon. Technol. Lett., vol. 10, pp. 549-551, 1998.

[3] M. K. Chin and S. T. Ho, "Design and modeling of waveguide-coupled single-mode microring resonators", J. Lightwave Technol., vol. LT-16, pp. 1433-1446, Aug. 1998.