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An Eight-Channel Demultiplexing Switch Array Using Vertically Coupled Active Semiconductor Microdisk Resonators

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***Abstract*—We demonstrate a 1.6-nm spectrally spaced eight-channel demultiplexer using active semiconductor microdisk resonators as a platform technology. Taking full advantage of the active microdisks, we are able to switch ON and OFF a resonator individually and tune the resonant wavelength as well by controlling the current injection levels. The use of active microdisks affords narrow spectral linewidth (<0.15 nm), low insertion loss (<2.5 dB), and distinct channel isolation (>15 dB) for the demultiplexed output signals.**

***Index Terms*—Active microdisk resonators, channel isolation, current injection, demultiplexer (DEMUX), photonic integrated circuits, spectral linewidth, switch.**

I. Introduction

CIRCULAR microresonators are of great interest in dense wavelength-division-multiplexing (WDM) applications due to their small feature size (radius <15 μm) and narrow spectral linewidth. In actual device configurations, the microresonator is either laterally [1] or vertically [2] coupled to the input–output (I/O) bus waveguides. The vertical geometry is advantageous over other structures because the material compositions and physical separation of the I/O bus and the resonator waveguides can be independently designed and controlled.

Active microdisks are important in particular since passive elements [3] have limited functionality in actual optical systems and require fabrication precision beyond the current state of the art. Optical losses or detuned resonant characteristics caused by fabrication imperfections can be compensated effectively by introducing an active design for the resonators. Moreover, active microdisks take full advantage of the versatile functionalities offered by microresonators. By implementing active materials into the microdisk, we have demonstrated tunable filters [4], gain and electroabsorption trimming modulators [5], [6], and continuous-wave bus-coupled microdisk lasers [7], [8].

In this letter, we present a 1.6-nm spectrally spaced eight-channel *demultiplexing switch array* using vertically coupled active microdisks as a platform technology. The suggested spectral channel spacing corresponds to the 200-GHz International Telecommunication Union grid spacing in optical WDM protocols. Current injection into the active gain material reduces the optical losses in resonators, which leads to narrow spectral linewidth and low insertion loss for the demultiplexed outputs. Also, the resonant wavelength of each microdisk can be tuned either with free carrier plasma effects or thermal effects by controlling the injection levels to meet the desired spectral channel spacing.

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II. Design and Experiment

The epitaxial growth by metal–organic chemical vapor deposition starts with a highly p-doped InGaAs contact layer, followed by the disk p-cladding materials that have decreasing doping in the layers to reduce free carrier absorption in the disk resonator. There are two vertically stacked waveguides: the active quantum-well (QW) disk core and the I/O bus waveguide, respectively, which are separated by a 0.8-μm-thick InP coupling layer. The disk core, with total thickness of 0.4 μm, consists of two *separate confinement heterostructure* (SCH) layers with $\lambda_{\rm SCH} = 1.25\ \mu$m ($n_{\rm SCH} = 3.36$ at $\lambda \sim 1500$ nm) and four QWs (0.5% compressively strained) with emission wavelength at $\lambda_{\rm QW} = 1.51\ \mu$m ($n_{\rm QW} = 3.48$ at $\lambda \sim 1500$ nm). Next, an n-doped InP coupling and I/O bus waveguide ($\lambda_{\rm BUS} = 1.1\ \mu$m, $n_{\rm BUS} = 3.29$ at $\lambda \sim 1500$ nm) layers are grown followed by a top n-cladding InP layer.

To initiate the device fabrication, I/O bus waveguides are lithographically defined and dry etched, and the entire structure is flipped over and thermally bonded to another InP transfer wafer. Then, the wafer-bonded sample is polished and the remaining InP from the original substrate is completely removed by selective chemical wet etching solutions. Smooth microdisk mesas with vertical sidewalls are produced on the exposed surface by using CH_4-based chemistry in a reactive ion etching discharge [9]. A conventional contact aligner is used to define the microdisk patterns where four pairs of different disk radii (r) are used to produce the eight resonators for our DEMUX. The disk radii are listed in Table I. After the device surface is planarized by photosensitive polyimide, electrodes are formed on the disks. The initial polyimide opening pattern defined on a disk mesa is smaller than the disk by 1.5 μm in radius, and it becomes enlarged to fit to the disk circumference as the polyimide is recessed toward the disk rim during a curing process. Then, the cured polyimide patterns having nearly the same radii as the disks are used as the openings for the electrodes, which is favorable for efficient carrier injection into the disk periphery region but very difficult to achieve when a conventional photolithographic alignment technique is used. Details on further processes can be found in [4]–[8]. Fig. 1(a) shows the schematic drawing of a unit active microdisk. Note

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TABLE I

MICRORESONATOR PARAMETERS FOR AN EIGHT-CHANNEL DEMUX. FOUR PAIRS OF DIFFERENT RADII ARE USED FOR EIGHT MICRODISKS. INTEGER m IS THE ASSOCIATED AZIMUTHAL MODE NUMBER. IN THE LAST COLUMN, THE RESONANT WAVELENGTHS OF MICRODISKS ARE ASSIGNED TO EIGHT CHANNELS, WHERE HIGHER CURRENT INJECTIONS ARE APPLIED ON CERTAIN MICRODISKS TO ACHIEVE THE DESIRED SPECTRAL CHANNEL SPACING. THE RESULTANT CHANNEL ASSIGNMENT IS SHOWN IN FIG. 3

Disk	r [μm]	n_{eff}	FSR [nm]	λ_{res} at $I = 6 \pm 0.4$ mA [nm]	Channel adjustment [nm]
1	9.6	3.168	11.5	1504.6 (m = 127)	1504.6 → Ch. 1
2	9.6	3.168	11.5	1516.1 (m = 126)	1515.5 (I = 7 mA) → Ch. 8
3	10.7	3.181	10.0	1506.2 (m = 142)	1506.2 → Ch. 2
4	10.7	3.181	10.0	1516.2 (m = 141)	1513.9 (I = 9 mA) → Ch. 7
5	12.3	3.200	8.4	1507.8 (m = 164)	1507.8 → Ch. 3
6	12.3	3.200	8.4	1507.8 (m = 164)	1509.4 (I = 10.5 mA) → Ch. 4
7	12.9	3.206	8.0	1510.9 (m = 172)	1512.4 (I = 11 mA) → Ch. 6
8	12.9	3.206	8.0	1510.9 (m = 172)	1510.9 → Ch. 5

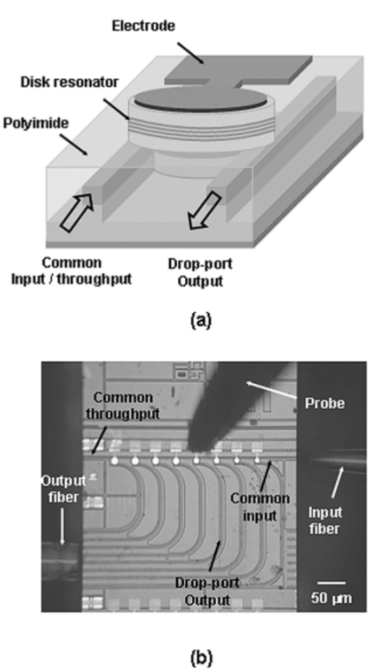

Fig. 1. (a) Schematic drawing of an active microdisk resonator vertically coupled to I/O bus lines. One of the bus channels is used for a common input–throughput waveguide, whereas the other one serves as an output drop-port. (b) Micrograph showing the top view of a fabricated eight-channel active microdisk DEMUX. Disk 4 (counted from the right end) is being measured in the micrograph.

that eight microdisk resonators are optically connected through a common input–throughput bus line.

III. RESULTS AND DISCUSSIONS

The optical resonant characteristics of an active microdisk are measured by coupling a transverse-electric polarized external

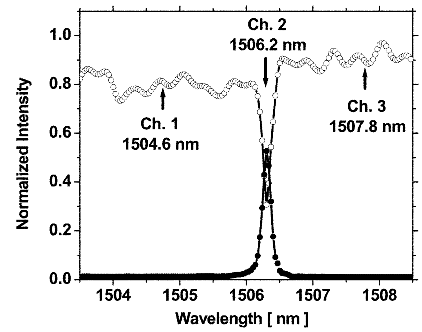

Fig. 2. Measured throughput (open circles) and drop-port (closed circles) resonant spectra of Channel 2 at $\lambda = 1506.2$ nm, for which only Disk 3 ($r = 10.7$ μm) is electrically pumped at $I = 5.8$ mA. Note that the unpumped microdisks remain absorptive so that only the resonant wavelength for Channel 2 appears in the common throughput spectrum and other optical channels are effectively "OFF."

tunable laser into the common input bus waveguide and collecting the transmitted (dropped) signal at the other end of the throughput (output) bus line. Fig. 1(b) shows an example of the measurement process on Disk 4.

A set of measured throughput and dropped output resonant spectra is given in Fig. 2, for which only the Disk 3 ($r = 10.7$ μm) is electrically pumped at $I = 5.8$ mA. Since the resonant characteristics are measured in the spectral range of QW bandedges, the microdisk is highly absorptive unless the resonator is electrically pumped. By fitting the measured data to the coupling of mode in time domain formula [1], we estimated the optical loss in the resonator (α), input $(\kappa_{\rm in})$, and output $(\kappa_{\rm out})$ coupling coefficients. As the current injection level varies from 0 to ~6 mA, α is reduced from 55 to 1.5 cm^{-1} and the resonator becomes nearly transparent in the spectral range of interest. The coupling coefficients are asymmetric as $\kappa_{\rm in} = 4\%$ and $\kappa_{\rm out} = 6\%$, respectively. Fabrication errors, such as slight microdisk–bus misalignments, may account for the asymmetric coupling. The estimated loss and coupling parameters predict a resonator insertion loss of 2–3 dB that is consistent with the measured ratio of the "OFF-resonance" throughput and "ON-resonance" output intensities. The typical linewidth at resonance is 0.15 nm that leads to a high quality factor (Q) of 10 000 at $\lambda \sim 1500$ nm.

It is worthwhile to observe the throughput response in Fig. 2, which shows that only the resonance from the microdisk under pumping is clearly distinguishable in the spectrum. Since the unpumped microdisks still remain highly absorptive, those resonators are not seen in the common throughput, and therefore, only the resonant wavelength of Channel 2 is coupled out to the drop port without affecting the other wavelength components. In a word, the active microdisk functions as an effective ON–OFF switching element that is operated by gain modulation with $I_{\rm full-extinction} =\sim 6$ mA.

Now we demonstrate the eight-channel demultiplexing characteristics of the fabricated active microdisk array. Initially, each microdisk is turned ON by injecting currents at approximately $I = 6$ mA and the resonant wavelength is measured as given in the fifth column of Table I. The resonant wavelength $(\lambda_{\rm res})$ of a microdisk resonator is determined by the resonant condition: $2\pi r n_{\rm eff} = m \times \lambda_{\rm res}$ (m is an integer), where $n_{\rm eff}$ is the effective modal index and r is the radius of a resonator. The disk radii are strategically designed in such a way that smaller-radii disks, having relatively larger free spectral ranges (FSRs), are assigned to the optical channels spectrally positioned at the shortest (Channels 1 and 2) and the longest wavelength (Channels 7 and 8) regions. This is to prevent any side-modes appearing in the middle of the spectral range containing the eight optical channels. For instance, Disks 1 and 2 ($r = 9.6\ \mu\mathrm{m}$) having FSRs of 11.5 nm are suited for Channels 1 and 8, since the FSRs are larger than the total spectral bandwidth of the 1.6-nm spaced eight channels ($1.6 \times 7 = 11.2$ nm).

At a glance, it seems preferable to design the disk radius even smaller in order to expand the FSR of each resonator. However, further reduction of disk radii causes several problems as follows: 1) The resonant wavelength becomes more sensitive to fabrication errors in physical dimensions. 2) Greater phase mismatch between the disk and straight bus waveguides reduce the coupling efficiencies. More sophisticated bus waveguide designs are required to extend the effective disk–bus interaction region for compensating the loss in coupling efficiencies. 3) The reduced resonator volume *increases the thermal resistance*, which limits the current injection in active microresonators. Therefore, a compromise disk radius is chosen, depending on the device fabrication and operation circumstances.

Once an active resonator is activated by pumping, the current injection level must be adjusted to tune the resonant wavelength at the desired spectral position. Free carrier injection into QWs cause band-filling and free carrier plasma effects, which affect the absorption coefficients of QWs and reduce the refractive index in the spectral range of interest. Therefore, the resonant wavelength of a resonator is blue-shifted with current injection [4]. As we further increase the injection levels, the cavity temperature is elevated and thermal effects, which shift the resonant characteristics back to longer wavelengths, become dominant [7]. In a word, a wide range of resonant wavelength tuning is achievable by varying the current injection levels. *For large radii* ($r > 12\ \mu\mathrm{m}$) *microdisks*, the maximum blue-shift tuning capability is -4 nm measured at $I = 9.5$ mA, while the resonant wavelengths are red-shifted up to $+3$ nm at $I = 12$ mA. Note that the tuning ranges are referred as the spectral shifts from the resonant wavelength at $I \sim 6$ mA where the microdisks are actually turned ON. The electrical power consumption associated with the current injection at the maximum achievable blue- and red-shift tuning are 13 and 19 mW, respectively. The smaller-radii microdisks exhibit slightly inferior blue-shit tuning capabilities, -3 nm at maximum for $r = 9.6\ \mu\mathrm{m}$, due to the higher thermal resistance. The tuning functionality highlights one of the most distinct advantages of using active microresonators over passive elements, because we can correct detuned characteristics caused by fabrication imperfections and achieve the desired channel spacing.

A complete set of demultiplexed output spectra for the eight-channel microdisk array is given in Fig. 3. The output spectrum of each channel is measured individually and the results are collected together in this figure. Note that $I = 6 \pm 0.4$ mA is applied to Channels 1, 2, 3, and 5, while $I = 10.5, 11, 9,$ and 7 mA are applied to Channels 4, 6, 7, and 8, respectively, as summarized in the last column of Table I. Here, the resonant modes for Channels 7 and 8 are deeply blue-shifted from their as-fabricated resonant wavelengths, whereas, those for Channels 4 and 6 are red-shifted by the thermal effects at higher current injection levels. As presented in Fig. 3, the desired channel spacing

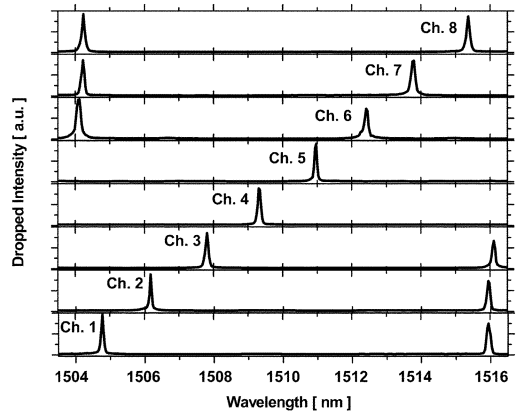

Fig. 3. Complete set of demultiplexed output spectra for eight-channels having 1.6-nm-spectral spacings. The resonant wavelength and current injection level of each microdisk are given in Table I.

(1.6 nm on average) is successfully achieved for the eight channels with a typical linewidth of 0.15 nm or less. The measured optical channel isolations are 15 to 20 dB. Since the optical isolation between channels is strongly affected by the lineshape of the adjacent channel, further improvement can be achieved by implementing multipole filter designs that offer high-contrast filtering with fast rolloff, instead of the classical Lorentzian response [10].

In conclusion, a 1.6-nm spectrally spaced eight-channel demultiplexing switch array has been realized by using active microdisk resonators as a platform technology. Taking full advantage of active microresonators, we can implement switching of each individual optical channel as well as precise control of the resonant wavelength by free carrier injection.

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