Compact Bandstop Filters with Semiconductor Optical Amplifier, Etched Beam Splitters and Total Internal Reflection Mirrors

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Abstract: Compact bandstop filters based on conventional waveguides, etched beam splitters, total internal reflection mirrors and integrated SOAs were demonstrated. 8.2 (14.5) nm free spectral range and 18 (12) dB extinction ratio are obtained for resonator of circumference 75 (45) μm.

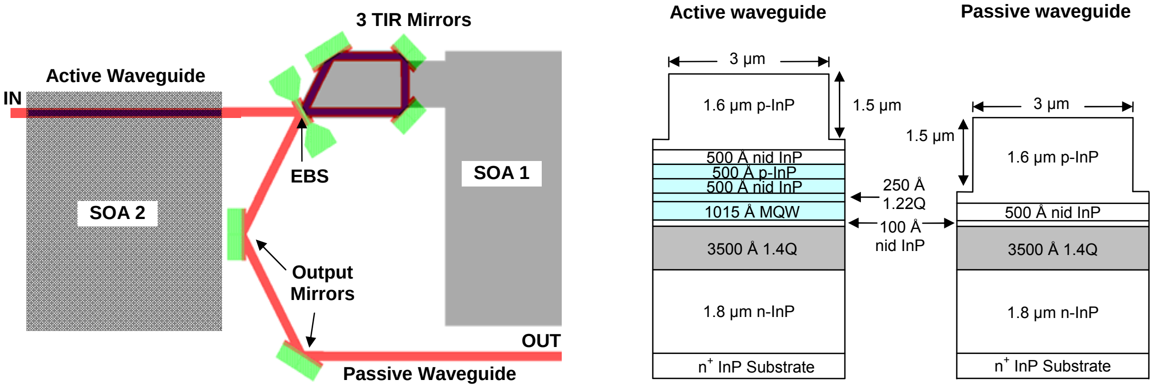
OCIS code: (130.7408) Wavelength filtering device; (220.4610) Optical fabrication

1. Introduction

Large free-spectral-range (FSR), high extinction ratio (ER), large transmission power, and narrow bandwidth (BW) are the some of the desired characteristics of bandstop filters based on ring resonators. Large FSR can be obtained using compact resonators since for a given material system FSR is determined by its circumference. Other characteristics are typically obtained near critical coupling condition [1, 2]. This means that resonator round trip loss, coupler loss, and power coupling should be properly balanced for better properties. Generally larger power coupling is required for increasing resonator round trip loss while absolute values depend on coupler loss. In our earlier work compact ring resonators were successfully demonstrated in GaAs/AlGaAs material system. This design used conventional semiconductor waveguides bent sharply using total internal reflection (TIR) mirrors [2, 3]. Coupling in and out was done using etched beam splitters (EBS) as submicron couplers. Both bandstop and bandpass operation were demonstrated [2, 3]. In this design waveguide propagation loss is negligible since resonator circumference is short. So the round trip resonator loss is mainly determined by loss of TIR mirrors and EBS and is independent of resonator size. Hence resonator circumference can be reduced without increasing resonator round trip loss. This improves the FSR without changing ER. In this work experimentally measured TIR mirror loss was less than 1 dB per mirror but EBS had relatively high loss due to the tightly confined vertical structure in the waveguide. In this case due to increased round trip loss larger power coupling is needed to approach critical coupling,. This in turn requires narrow EBS gap, which makes fabrication more difficult due to higher aspect ratio. Furthermore slight changes in the gap dimension can affect power coupling and filter characteristics significantly. In the extreme case of high loss device may not work at all. One approach to solve this difficulty is to use a weakly guiding structure in vertical direction to reduce EBS loss [4]. But this requires a very deeply etched narrow gap EBS, which makes fabrication difficult. The other approach is to use a semiconductor optical amplifier SOA with electrically adjustable gain integrated inside the resonator to adjust the round trip loss. This paper reports the design, fabrication and characterization of such compact bandstop filters in InP platform.

2. Device Description and Fabrication

Figure 1 (a) shows the top schematic of designed bandstop filter. The resonator is formed using one EBS that serves as the coupler, and three TIR mirrors that fold straight waveguides into a trapezoidal shape resonator. Our earlier work showed that one can get appreciable transmission from an EBS as wide as 0.5 μm for angles of incidence a few degrees above the critical angle [2, 3]. For an air filled EBS the critical angle in compound semiconductors is about 16º. We fill the trench with Benzocylobutane (BCB) of index 1.53 to increase the critical angle to about 30º. This increase actually helps to reduce the circumference of the resonator. Using geometrical arguments it can be shown that using 3 μm wide waveguides and BCB filled EBS the circumference can be reduced to 45 μm. This corresponds to a free spectral range (FSR) of about 15 nm. Inside the resonator there is an integrated SOA (SOA 1) used to compensate resonator loss and tune the resonator characteristics. The resonator output is directed to a cleaved facet using two output TIR mirrors for convenient measurement. Input waveguide has a 2 mm long integrated SOA section labeled SOA 2. SOA 2 is used to boost the input power before the resonator. It is also used as an integrated broadband light source during measurements. In order to minimize the undesired reflections from the cleaved facets input and output waveguides are 7º tilted near cleaved facets and facets are anti-reflection coated. The cross sectional profiles of active and passive waveguides are shown in Figure 1 (b). Both waveguides are 3 μm wide rib waveguides etched 1.5 μm deep into p-InP layer. They basically use same layer structure for vertical mode confinement. 3500 Å thick core layer is sandwiched in between InP layers. The core layer is a quaternary with bandgap corresponding to 1.4 μm. Active waveguides contain multi quantum wells (MQWs) designed for maximum gain near 1550 nm. They are grown on the core layer during the initial base structure growth. The base epitaxial wafer consists of n-InP layer, core layer and active MQW layer as shown in the active waveguide structure. To form passive waveguides, QWs are selectively etched away. This is followed by the regrowth of a 1.6 μm thick p-InP on both active and passive waveguides. Having MQWs on top of the core leaves core untouched and does not change core dimension during regrowth. Hence the overlap between the active and passive waveguide sections improve significantly. This in turn minimizes coupling loss and reflection between active and passive waveguides.



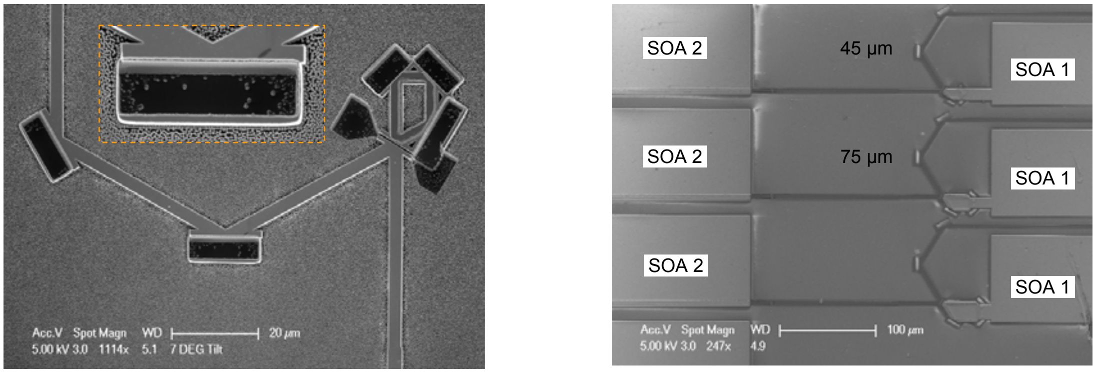
(a) **(b)**

Figure 1. (a) Schematic of bandstop filter using EBS, TIR mirrors and SOA, and (b) cross sectional profiles of the active and passive waveguides used in the experiment.

During fabrication first, active waveguide region was defined by selectively etching the MQW layer in the base structure using a Si_3N_4 mask. This is followed by regrowth of the p-cladding layer. Then contact metal (Pd/Zn/Pt/Au) were defined and annealed. Next the entire surface was covered with 6000 Å thick SiO_2, which was main etching mask during following etching steps. After this step, all patterns including waveguide, EBS and TIR mirrors, were patterned by lifting off a 500 Å nickel mask. EBS and TIR mirrors were defined by e-beam lithography to obtain finer edges and sub micron dimensions. The rest of the structure containing long waveguides were patterned by standard photolithography. During etching first SiO_2 was etched using the nickel mask with reactive ion etching (RIE). Next InP is etched with RIE to form the waveguides. In this step p-cladding layer is etched to a depth of 1.5 μm. After waveguides were etched, another 6000 Å SiO_2 film was deposited over the entire sample and areas which would be deeply etched to form the EBS and mirrors were opened. The required mask is fabricated by lifting off a second nickel mask. This was followed by deep-trench etching using inductively coupled plasma (ICP) RIE with H_2: Cl_2: Ar. Then remained SiO_2 etching mask was fully removed by using HF. Figure 2 (a) shows fabricated devices up to this step. A very smooth TIR mirror surface was obtained as shown in the insert. Then BCB was spin-coated and fully cured for trench filling and planarization. Next BCB is etched-back to expose ohmic contact metals on active waveguides. Finally pad electrode is formed with 1 μm thick Au liftoff. After cleaving the device, an antireflection coating of Ta_2O_5 is applied to each facet. The fabricated devices are shown in Figure 2 (b).

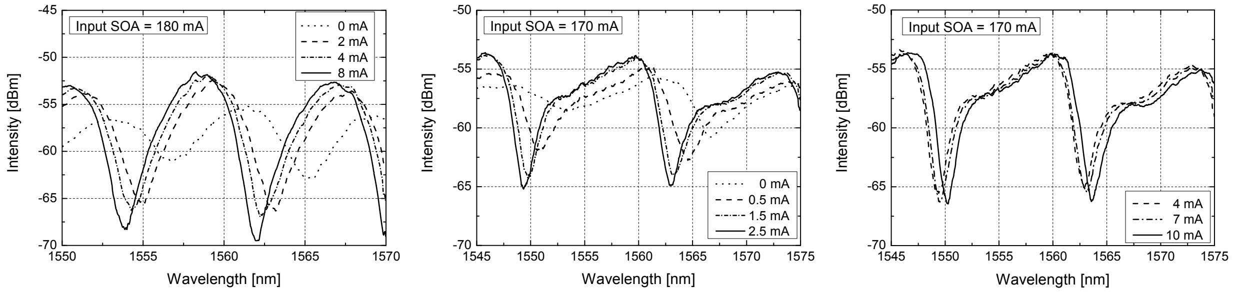
3. Measurements

For measurements outside SOA (SOA 2) is biased and used as broadband source. The power variations of this broadband emission are calibrated by measuring the emission of SOA 2 through the other facet during measurements. Figure 3 (a) shows the output spectrum of the resonator with circumference of 75 μm for different injection currents of SOA 1 when the bias current of the SOA 2 is 180 mA. The EBS is 0.4 μm wide and angle of incidence is 31°. This response clearly shows bandstop characteristics with FSR of 8.2 nm. Without current injection, SOA inside resonator acts as an absorber and degrades filter characteristics by unbalancing the resonator. When SOA 1 current is increased, it begins to provide gain and compensate resonator loss. This enhances filter characteristics such as bandwidth, maximum transmission and extinction ratio (ER). At a current of 8 mA, ER increases to 18 dB, which is an 11 dB enhancement compared to no current case. The resonant wavelength also shifts to shorter wavelengths because refractive index of waveguide inside resonator decreases due to current injection.



(a) (b)

Figure 2. SEM picture: (a) blow up of output TIR mirrors and resonator with circumference of 45 µm before BCB filling, and (b) fabricated devices.



(a) (b) (c)

Figure 3. Measured optical spectrum of resonator for different injection current of SOA 1: circumference of (a) 75 µm and (b-c) 45 µm.

The filter characteristics of 45 µm long resonator are shown in Figure 3 (b)-(c) for different SOA 1 currents. The EBS is 0.5 µm wide and angle of incidence is 29º. The current of SOA 2 is fixed at 170 mA. When current of SOA 1 is 2.5 mA, ER of 12 dB and FSR of 14.5 nm are obtained. The resonance first shifts to shorter wavelengths as observed in 75 µm long devices but it moves to longer wavelength with injection current larger than 4 mA as shown in Figure 3 (c). This is due to increase of refractive index as device temperature increases. For both types of resonators filter characteristics is observed even with no SOA 1 bias. This indicates the round trip loss is low. Complete characterization of TIR mirrors and EBS is underway and further results will be given at the conference.

4. Summary

We have designed, fabricated, and measured compact bandstop filters based on conventional waveguides, EBS and SOA in InP platform. The circumference of resonator is reduced to 45 µm using EBS and TIR mirrors. The extinction ratio of 13 dB and free-spectral range of 14.5 nm are obtained with 2.5 mA of current injection to the SOA inside the resonator of 45 µm circumference. The resonator with circumference of 75 µm shows 18 dB ER and 8.2 nm FSR at 8 mA bias current.

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