InGaAsP/InP Vertical Directional Coupler Filter with Optimally Designed Wavelength Tunability

Chi Wu, C. Rolland, F. Shepherd, C. Larocque, N. Puetz, K. D. Chik, and J. M. Xu

Abstract—**A broad electrotuning range (> 73 nm) and narrow bandwidth (~ 1.5 nm) InGaAsP/InP tunable directional coupler filter, employing two vertically coupled asymmetric ridge waveguides, has been designed and demonstrated. It operates with both current injection and electrorefraction. This is the widest tuning range reported to date for a semiconductor waveguide filter and is obtained with a moderate current level (~ 1.1 kA/cm^2). The tuning range can be extended to (> 80 nm) if the thermal tuning is included.**

INTRODUCTION

THE use of wavelength-division-multiplexing/demultiplexing (WDM) techniques in optical communication networks will increase the transmission capacity of existing fiber links, thus taking full advantage of the wide low-loss window available in optical fibers. Narrow-bandwidth, wavelength selective, broad-range tunable filters based on InGaAsP/InP are potentially key devices for wavelength and optical switching in optical communication systems. In addition, the device could be made compatible for monolithic integration with other optoelectronic components, such as optical amplifiers or receivers. Recently, a broadly tunable (21.5 nm), narrow bandwidth (2.0 nm), grating-assisted directional coupler filter with a central wavelength around 1.5 μm, device length of 2 mm and a tuning current density of 5.5 kA/cm^2 has been demonstrated [1]. Using quantum well electrorefraction, wavelength tuning in a grating-assisted vertical coupler filter has also been observed in AlGaAs/GaAs [2]. A large tuning range is expected using the quantum-confined Stark effect; however, a value of only 2.0 nm was achieved with a −3 dB bandwidth of 1.7 nm. By monolithic integrating an optical amplifier with a grating-assisted directional coupler filter [3], [4], an intracavity tunable laser has been obtained with tuning range of 57 nm in the 1.5-μm low-loss window and bandwidth of 3.0 nm using both forward and reverse biases [4]. In this letter, we report on the experimental demonstration of a widely tunable (> 73 nm), narrow bandwidth (~ 1.5 nm), low injection current density (~ 1.1 kA/cm^2), vertically coupled ridge waveguide directional coupler filter. The device operates at a central wavelength around 1.3-μm and is 5-mm long. In addition, the structure is simple to fabricate, requiring only a single growth and etch step.

PRINCIPLE OF OPERATION

A schematic diagram of the device is shown in Fig. 1 with the corresponding layer thicknesses. The filter consists of two vertically coupled waveguides of dissimilar cross sections and different quaternary compositions. The upper waveguide layer is thin and made of a high refractive index material while the lower waveguide is designed to have a thicker layer, but with a lower refractive index. The propagation constant β_t and β_b of the individual upper and lower waveguide will be identical for a certain wavelength, λ_o, at which light launched into the lower guide will be completely coupled to the upper guide after traveling a coupling length, L_c. As $|\lambda - \lambda_o|$ increases, the coupling between the two waveguides weakens rapidly due to phase mismatch. This is the basis for a directional coupler to function as a wavelength filter. According to the coupled mode theory [5], the bandwidth at half maximum $\Delta\lambda_{BW}$ is given by

$$\Delta\lambda_{BW} \approx \frac{5}{L_c \sigma_\lambda} \tag{1}$$

where σ_λ (the differential dispersion of the propagation constant) is equal to

$$\sigma_\lambda = \left[\frac{d\beta_t}{d\lambda} - \frac{d\beta_b}{d\lambda}\right]_{\lambda=\lambda o}. \tag{2}$$

From (2) the filter bandwidth will be narrow if the dispersion in one waveguide is large compared to the other one. This condition is fulfilled with the use of a strongly (top) and a weakly (bottom) confined waveguide as shown in Fig. 1.

A p-i-n junction is located in the upper guide to allow an index change by either current injection or electrorefraction. The former provides a negative index change

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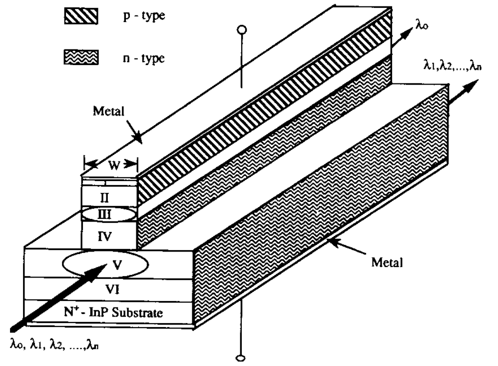

	Thickness(μm)	Material
Layer I	0.2	p^+ - InGaAs
Layer II	1.2	p - InP
	0.05	i - InP
Layer III	0.28	i - InGaAsP (λ_{g2}=1.2-μm)
Layer IV	2.05	n - InP
Layer V	0.8	n - InGaAsP (λ_{g4}=1.04-μm)
Layer VI	1.5	n - InP

Fig. 1. Schematic view of the tunable vertical directional coupler filter.

whereas the latter contributes to a positive index change. When the refractive index in the upper guide is altered by either of these effects, the phase matched condition $\beta_t(\lambda_o) = \beta_b(\lambda_o)$ is no longer met. Instead, a new phase matched condition $\beta_t(\lambda'_o) = \beta_b(\lambda'_o)$ will be established. The wavelength tuning of $\Delta\lambda_T$ is given by [6]

$$\Delta\lambda_T = \lambda_o - \lambda'_o = \frac{\Delta\beta_t}{\sigma_\lambda} \tag{3}$$

where $\Delta\beta_t = \beta_t(\lambda_o) - \beta_t(\lambda'_o) = \Gamma_t \Delta n_t k_o$ is the change in propagation constant of the upper guide. Γ_t and Δn_t are the optical confinement factor and refractive index change of the bulk material in the upper guide, and k_o is the free space wave vector. Since, both $\Delta\lambda_{\mathrm{BW}}$ and $\Delta\lambda_T$ are inversely proportional to σ_λ, it is possible to design a device with a very broad tuning range by using two similar waveguides. However, the filter bandwidth will also become very large.

To increase the number of channels for system applications, a filter should have both a broad tuning range and a narrow bandwidth. Therefore, it is necessary to look at a normalized tuning range T_b:

$$T_b = \frac{\Delta\lambda_T}{\Delta\lambda_{\mathrm{BW}}} = \frac{\Delta\beta_t L_c}{5}. \tag{4}$$

The challenge is to design a device with a large T_b. From (4), it appears that long coupling length can increase T_b indefinitely. However, there exists a limitation for a tunable filter using current injection. When the free carrier induced loss in the upper guide is comparable with the coupling coefficient κ of the coupler ($\kappa L_c = \pi/2$), the even and odd modes experience significant different propagation losses. This effect leads to an incomplete cancellation of the normal even and odd modes in the feed-in guide for any traveling distance. As a result, the directional coupler would fail to operate. Since both the optical loss and the refractive index change are proportional to the free carrier concentration in the upper guide, there is a tradeoff design between $\Delta\beta_t$ and L_c [7]. We have carried out an optimum design for T_b for a narrow bandwidth. The design approach is similar to that published in [8].

DEVICE FABRICATION AND RESULTS

The device was grown by metalorganic chemical-vapor deposition (MOCVD). The ridge width (W) is chosen to be 2 μm. The structure is etched down to the middle of the separation layer by reactive ion etching followed by a selective chemical etch to stop at the lower guide interface. Following a Si_3N_4 thin film deposition, a window to the p^+-InGaAs is open by a reactive ion etching (RIE) and Ti/Pt/Au is evaporated to form the p-contact. The wafer is then thinned and the back n-contact evaporated. After cleaving into 5-mm bars, the device is AR-coated.

The performance of the device is measured with a tunable narrow linewidth semiconductor laser (SANTEC TSL-80) driven by a pulse generator at 98 Hz for lock-in detection. Using a 90/10 splitter fiber, 90% of the laser light is sent to the tapered end for butt coupling to the waveguide, while the remaining 10% of laser light is sent to an optical spectrum analyzer to monitor the incident power and the wavelength. The output of the ridge waveguide is imaged with a 63 × objective onto an infrared camera and a Ge photodetector. An aperture is used to isolate light between the lower and upper guide, as well as to isolate the stray light. For convenience, we couple the input radiation into the upper guide and measure the output from the lower guide to avoid the significant spontaneous emission which occurs in the upper guide at high injection currents. This method enable us to quickly find the optimum coupling wavelength for a given injection current using a vidicon, since the spontaneous emission present in the upper guide can be visually eliminated with an aperture.

The interwaveguide coupling efficiency is plotted in Fig. 2 as a function of wavelength for TM polarization at two tuning currents: $I = 0$ and 20 mA. The interwaveguide coupling efficiency is defined as [2]

$$\eta = \frac{P_b}{P_t + P_b} \tag{5}$$

where P_t and P_b are the outputs of optical powers from feed-in guide and branch-guide, respectively. For zero bias, the central wavelength is at 1.3165 μm with a −3 dB bandwidth of 1.5 nm and an interwaveguide coupling efficiency of more than 90% is observed. With an injection current of 20 mA, the central wavelength shifts to shorter wavelengths since the current reduces the refractive index in the higher index upper guide. The −3 dB bandwidth becomes slightly narrower while the base of the filter passband becomes wider due to an increase in loss. The variation in the interwaveguide coupling efficiency is caused by a change in the coupling length and

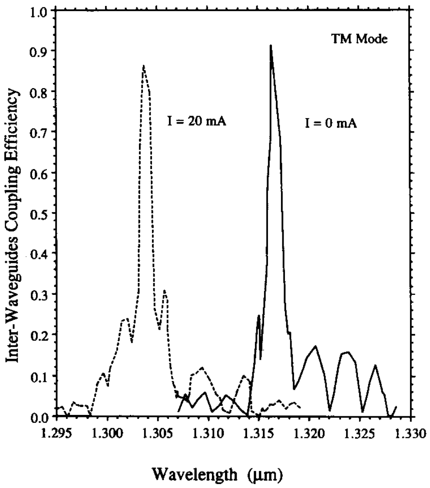

Fig. 2. Measured filter response of the inter-waveguide coupling efficiency for the TM mode at tuning currents of $I = 0$ and 20 mA, respectively.

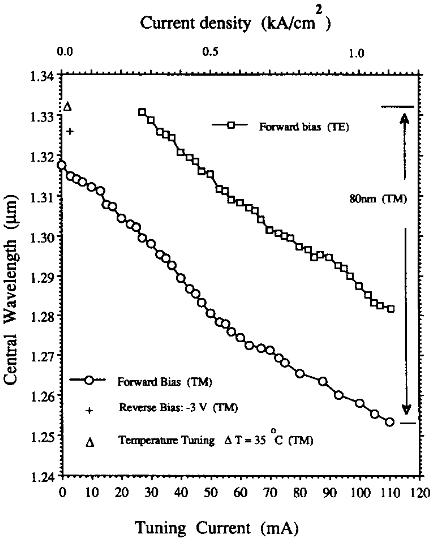

Fig. 3. Measured change in the filter central wavelength versus tuning current (and estimated current density), for a −3 V reverse bias voltage and a 35°C temperature change. The device is usually tested at 20°C for both TE and TM modes.

waveguide losses. The worst coupling efficiency over the entire tuning range is about 60%. Fig. 3 shows the measured filter central wavelength versus dc tuning current (and estimated current density) for both TE and TM modes. For most of the measurements, the device temperature was kept at 20°C with a thermoelectric cooler. For a current density up to 1.1 kA/cm^2, a wavelength tuning of 64 nm was measured for the TM mode. With the application of a reverse bias voltage in the upper waveguide, the refractive index increases due to electrorefraction and the filter peak shifts to longer wavelengths. At −3 V, the central wavelength moves by 8.6 nm. Using both forward and reverse bias, an electronically controlled tuning range of 73 nm has been obtained. This gives an electronically controlled normalized tunability of T_b = 73 nm/1.5 nm = 48.6. Finally, we note that thermal effects contributes to a positive index change which results in a wavelength change at a rate of 0.4 nm/°C. The combination of these various effects brings to 80-nm the total tuning range of the filter for TM polarization. A similar behavior was observed for TE polarization, except for a 30-nm shift of the filter peak wavelengths. This dependence on polarization could be used for a TM/TE splitter device.

The tuning range of the filter could be further expanded by injecting higher current, since the tuning curve of Fig. 3 is not saturated at injection current density of 1.1 kA/cm^2. Presently, our measurements are limited by the wavelength range of our light source. A more fundamental limitation is the decrease in coupling efficiency due to changes in the coupling length and the larger absorption losses (free carriers and electroabsorption) in the upper guide. The integration of a gain section with this filter could compensate such losses.

CONCLUSION

A tunable InGaAsP/InP ridge waveguide vertical directional coupler filter has been designed and fabricated with an electronically controlled large tuning range, > 73 nm, and a −3 dB bandwidth of 1.5 nm. This is the widest tuning range ever reported for a semiconductor waveguide filter. It also has the largest normalized tuning range of T_b = 48.6. The device has potential use as a wavelength tunable switch (drop or add) or a polarization splitter.

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