ALL-ACTIVE InGaAsP/InP RING CAVITIES FOR WIDESPREAD FUNCTIONALITIES IN THE WAVELENGTH DOMAIN

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Abstract

All-active ring resonator structures allow filter operation as well as laser mode operation, only depending on the driving conditions. Add/drop filter devices based on active InGaAsP/InP have been realized for the 100 and 50 GHz free spectral range. The properties of all pass-filter elements built of active single ring resonators are investigated. A delay time up to 80 ps has been measured for a bending radius R of 250 µm and a coupling ratio of 0.6 to the bus-waveguide. The respective dispersion of ±280 ps/nm is attained within a pass band of 5 GHz. Operating in the laser mode, microring resonator structures with R =50 µm show a single mode emission spectrum with an optical power output as high as of 6.5 mW per facet.

I. Introduction

Growing interest for photonic microring resonators is caused by their novel device properties and an inherently high potential for higher scale integration. Multistage wavelength filters and all-pass filters for dispersion compensation based on ring resonators are under investigation for TDM/WDM network applications[1,2]. Active devices like microring lasers[3] and ring resonator wavelength converters[4] are promising applications for communication purposes. This contribution reports on ring resonator devices built in InGaAsP/InP and acting as adjustable wavelength filters, optical delay lines and also as single mode laser sources.

II. Device design

Our active ring devices are based on an $In_{1-x}Ga_xAs_{1-y}P_y$ strained layer multi-quantum well (MQW) gain structure embedded between quaternary waveguide layers. The 1.8 µm ridge type waveguides are formed by reactive ion etching. A two-level etching process is applied to increase the index step at the outer side of the bent waveguides (Fig. 1). The deeply etched outer facet assures sufficiently low bending losses for radii smaller than 100 µm. The ring cavities under investigation here have a race-track shape with straight sections for the coupling to the bus waveguides (Fig. 2). Depending on the required functionality different types of couplers have been designed. Multi-mode interference couplers were applied for an intentional power split of 3 dB. Co-directional couplers of different length have been used to accomplish also other coupling ratios, where a gap of 0.8 µm has been realized. The half circle radii result directly from the coupler length L_c since the overall circumference length L is fixed for a specified free spectral range (FSR). We have used coupler lengths ranging from 70 to 200 µm, the bend radii varied from about 50 to 500 µm.

If the electrical contacts are well separated all functional parts of the active ring resonator devices can be controlled individually. We could minimize the cross-talk between the segments by a gap in the Au-contact layer on top of the p-InP ridge. In this way, a contact separation better than 300 Ω has been achieved.

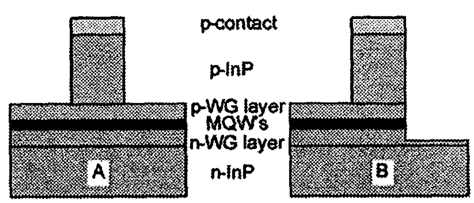

Fig. 1. Cross sectional view (schematic) of the active layer waveguides; A: straight waveguide (coupler structures have the same vertical etching stop on top of the quaternary p-waveguide layer), B: asymmetric index step of the curved waveguide due to a deeply etched region at the outer facet

Our gain material favors TE emission, therefore the presented properties of the ring resonators are shown for excitation with TE polarized light. In general, very similar results are expected for both TE and TM polarization modes. However, the development of polarization insensitive gain material is a task in its own right.

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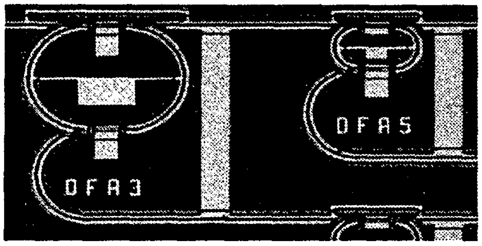


Fig. 2. Part of a possible interleaver device based on active ring resonators showing the 50 GHz and 100 GHz FSR stage

III. Ring resonators with gain or loss - modes of operation

The general properties of an active single ring resonator can be described within a simple parametric model[5]. Assuming a point coupling and considering the net gain or loss in the ring via an amplitude factor

$$\alpha_0 = \exp(-gL/2)$$

(g – power loss/gain coefficient), the resulting transfer function of the optical field in the coupled bus waveguide is

$$T_1(\lambda) = \frac{(t-\alpha(\lambda))}{(1-\alpha(\lambda)t)} \text{ where } E_{out}(\lambda) = T_1(\lambda)E_{in}(\lambda)$$

with $E_{in}(\lambda)$, $E_{out}(\lambda)$ are the incoming and outgoing optical field components in the bus waveguide, t represents the absolute value of field transmission in the coupler region and

$$\alpha(\lambda) = \alpha_0 \exp(i2\pi nL/\lambda)$$

(n – effective index) describes the field modulation along the ring path.

At the resonance wavelengths $\lambda_{r,m} = 2nL/m$ ($m = 1, 2, \ldots$), the field in the ring interferes constructively after one circumference. At these wavelengths the power transmission $T(\lambda) = |T_1(\lambda)|^2$ in the bus waveguide shows a minimum or a maximum depending on whether the field amplitude is reduced ($\alpha_0 < 1$) or increased ($\alpha_0 > 1$) along the ring path, with $\alpha_0 = 1$ the transmitted power remains constant. The FSR which is the distance between the resonance points, is given by the group index and the resonator length L. The situation is illustrated in Fig. 3.

In our experiments we could verify the predicted behavior[6]. For example, the measured transmission spectrum of a single ring resonator with an FSR = 50 GHz is shown in Fig. 4. By varying the ring current and hence varying net gain and loss parameters, the transmission spectrum is changed.

It has to be noted that the presented approach using an all-active structure differs from a similar architecture of filter devices[7] introduced earlier. Formerly, separate gain sections are placed in ring resonators for loss compensation, whereas the overall device was built of passive semi-insulating material. With the all active devices we now have a smaller number of epitaxial growth steps and, in addition, an increased functionality. For example, the separate driving of device sections, also of the bus waveguide, can be used to reduce the insertion loss.

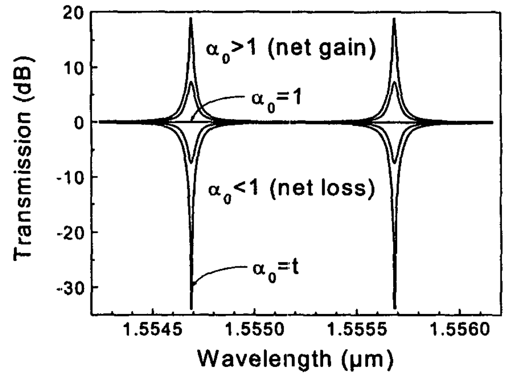


Fig. 3. Transmission characteristic of a single ring device for different amplitude factors α_0

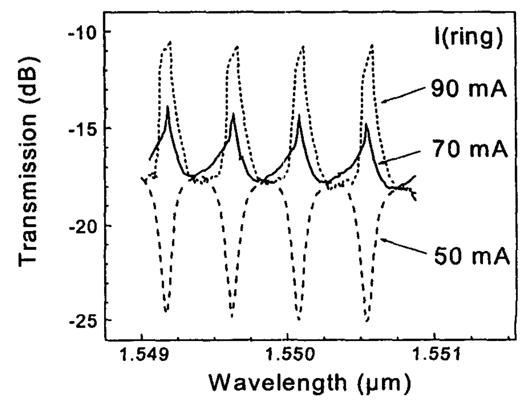


Fig. 4. Transmission characteristic of an active ring resonator under different driving conditions

Based on these general relations different states of operation can be obtained which are of particular interest for applications.

(1) Critical coupling: A ring resonator coupled to a bus waveguide acts as a wavelength filter, when a net loss of power occurs after one circumference ($\alpha_0 < 1$). The highest ratio of on/off resonance transmission is achieved under the condition of $t = \alpha_0$. Then, the transmitted power becomes zero at the resonance wavelengths. This situation is called "critical coupling".

(2) All-pass filter: For $\alpha_0 = 1$ the ring filter is no longer a filter in the wavelength domain. The power transmission $T(\lambda)$ becomes unity for all wavelengths. However, the impulse response in the time domain results in a nonlinear delay time with

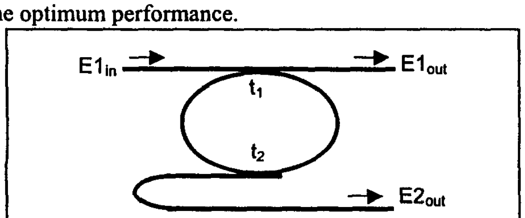
positive or negative slope for signals near the resonance wavelengths. The effect can be used for application in optical delay lines as well as for dispersion compensation.

(3) Ring laser: With a net gain ($\alpha_0 > 1$) the lasing threshold is reached for resonant wavelengths at $t^*\alpha_0 = 1$. In comparison with conventional lasers, these ring lasers need no reflecting facets or other feedback structures and hence, are well suited for integration concepts.

IV. Applications

Add/drop filter

To realize an add/drop element for wavelength filtering, the ring resonator has to be coupled to two bus waveguides (Fig. 5). Compared to the transfer function $T_1(\lambda)$ the respective relation for the throughput port is slightly modified. It takes into account the additional power loss in the ring caused by the coupler to the drop port. It is obvious, that for two identical couplers ($t_1 = t_2$) the condition (1) of critical coupling for the throughput port is simply fulfilled when $\alpha_0 = 1$. If different couplers are used ($t_1 \neq t_2$) condition (1) can be accomplished with $\alpha_0 = t_1/t_2$. Hence, by tuning the amplitude factor via the ring current, the filter characteristic can be adjusted to the optimum performance.



$$E1_{out} = T_{through}(\lambda)E1_{in} = \frac{(t_1 - \alpha(\lambda)t_2)}{(1-\alpha(\lambda)t_1t_2)}E1_{in}$$

$$E2_{out} = T_{drop}(\lambda)E1_{in} = \frac{-\alpha'(\lambda)\sqrt{(1-t_1^2)(1-t_2^2)}}{(1-\alpha(\lambda)t_1t_2)}E1_{in}$$

Fig. 5. Model of the single ring add/drop filter element and transfer functions for the throughput port ($T_{through}$) and the drop port (T_{drop}); $\alpha'(\lambda)$ is the field modulation in the ring section between coupler 1 and 2

In the case of critical coupling, the ratio of on/off resonance intensity in the drop port is derived to

$$D = \frac{4t_1^2}{(1-t_1^2)^2}.$$

That means, D is only determined by t_1, the field transmission of coupler 1 in the throughput port. In order to achieve high on/off ratios in both the throughput and the drop port a weak coupling to the bus waveguide has to be realized.

By using active ring resonators with specific circumference lengths add/drop filters have been fabricated for free spectral ranges fitting the channel spacing in WDM systems. Fig. 6 shows, as an example, the filter characteristic of a device with 100 GHz FSR. Based on active ring resonators, a compact (1mm x 2 mm) interleaver network can be designed for demultiplexing from 25 GHz to 100 GHz by a series of add/drop filters with different FSR. (Fig. 2).

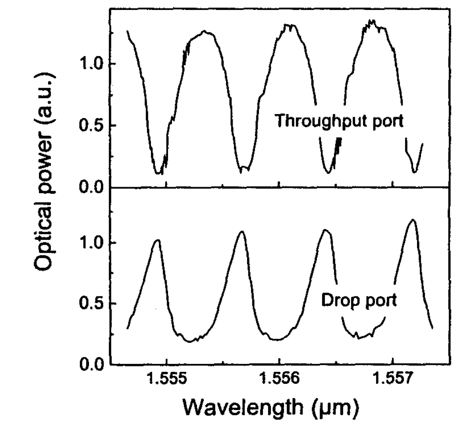


Fig. 6. All-active ring resonator as an add/drop demultiplexer. FSR = 100 GHz

Optical all-pass filters

The phase corrections introduced by all-pass filters (operating regime (2)) come without amplitude distortion and are of increasing interest for dispersion compensation in TDM/WDM systems and delay line applications.

Considering the phase $\Phi(\omega)$ of the complex transfer function in the frequency domain, the group delay τ_d is defined as[8]

$$\tau_d = -\frac{d\Phi(\omega)}{d\omega}.$$

All-pass ring filters are infinite impulse response filters, where the feedback path is resonantly increased. The nonlinear delay time depends on the circumference length L and on the coupler properties (i.e. on the parameter t).

We have investigated the delay time introduced by our ring filter devices as a function of wavelength. By using an external cavity laser combined with an optical modulator a 1 GHz sinusoidal probe signal was generated. The time delay caused by the ring resonator device was measured with respect to a reference signal.

Experimental results obtained for a 50 GHz active ring resonator are shown in Fig. 7. The delay time peaks up to around 80 ps at the resonance wavelengths. Close to the resonance wavelengths a dispersion slope of ±280 ps/nm was obtained within a bandwidth of 5 GHz. This result agrees well with the simulated impulse response for a ring filter element including a co-directional coupler with a power coupling ratio of $C = 1 - t2 = 0.6$. By building multistage all-pass filter devices the delay time can be further increased, in addition, a desired dispersion slope may be adjusted[8].

An on/off ratio of only 3 dB in the intensity response (Fig. 7) is indicating a remaining net loss in the ring. Unfortunately, a further increase of ring current lead to problems caused by the feedback from the facets, indicating a non ideal AR-coating. Additional experiments will be done to overcome this problem.

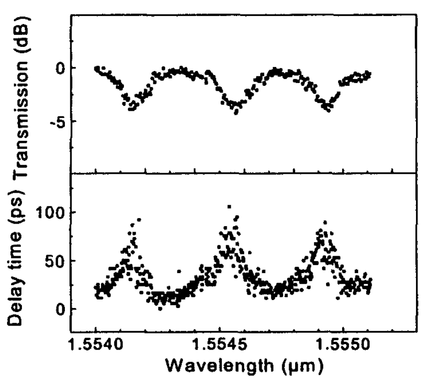


Fig. 7. All-pass filter characteristic of a 50 GHz active ring filter, delay time is measured for a 1 GHz modulated wavelength source

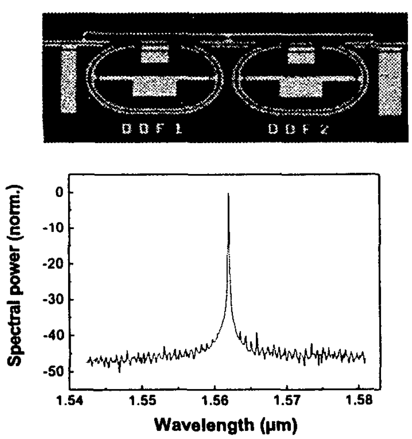


Fig. 8. Single mode emission spectrum of a ring laser structure

Single mode ring laser

At driving levels as high as $\alpha_0 t = 1$ the lasing threshold is reached (regime (3)): Similar to a straight Fabry Perot cavity, the ring generates a comb spectrum of longitudinal laser modes. Single mode operation is predicted for very short cavity length, i.e. for small ring radii. In other concepts[9] passive ring resonators are used for mode selection purpose.

In our case, we could realize a single mode laser with two active rings (R = 50 μm) as coupled resonators (Fig. 8). The emission spectrum of this structure reveals a high side mode suppression ratio of > 40 dB. A power output of 6.5 mW (@250 mA) was attained per facet.

V. Summary

We have realized filter and laser operation of active ring resonators based on InGaAsP/InP gain structures. An add/drop function and optical all-pass filter characteristic have been demonstrated by using a single ring resonator. Single mode laser operation was achieved with a double ring resonator. The functionalities of active ring resonators underline their wide potential of application in optical communication systems.

Acknowledgement

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