Further miniaturized retro-reflector cavity semiconductor micro-ring lasers

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***Abstract*— Novel retro-reflector cavity semiconductor ring lasers have been designed to achieve micro-sized devices. Fabricated devices lase CW at room temperature and demonstrate clear bistability down to 16μm radius. The retro-reflector is further miniaturized for smaller devices of < 10μm radius and proofed in CW lasing ring lasers.**

Keywords - semiconductor ring laser; integration; mirror; retro-reflector.

I. INTRODUCTION

Recently, semiconductor ring lasers (SRL) have attracted much interest because they offer switching, regeneration, digital and memory potentials suitable for all optical signal processing [1-4]. The intuitive circular and racetrack devices exhibit strong directional bistability [5-7]. To decrease the device size, these cavities may encounter several problems including backscattering, current leakage, and low output coupling ratio due to the strong optical confinement by the deep-etched ridge waveguides in a circular cavity. These problems can be avoided by combining shallow-etched ridge waveguides with carefully designed mirrors to form rectangular ring cavities. Here the design and fabrication of the mirrors are key to achieving not only low optical loss, but also to achieve low optical back-scattering, as back-scattering is detrimental to the directional bistability of the SRL on which all digital functions are based.

We have used a novel parabolic mirror retro-reflector (RR) mirror design instead of the conventional waveguide total internal reflection (TIR) mirror for this purpose. Two parallel straight shallow ridge waveguides (RWGs) are connected by two RR mirrors to form a closed cavity. The size of SRL can be significantly reduced while maintaining the benefits of low current leakage in the RWGs and minimizing the optical loss caused by conventional TIR mirrors. The key to this proposed SRL structure is the optimisation and fabrication of the RR mirrors.

II. RETRO-REFLECTOR MIRROR DEISGN

In our initial design, the two RWGs are placed in parallel 20 μm from each other (Fig. 1(a)). These waveguides terminate by widening abruptly, leaving the optical beam unconfined horizontally as they enter the body of the RR.

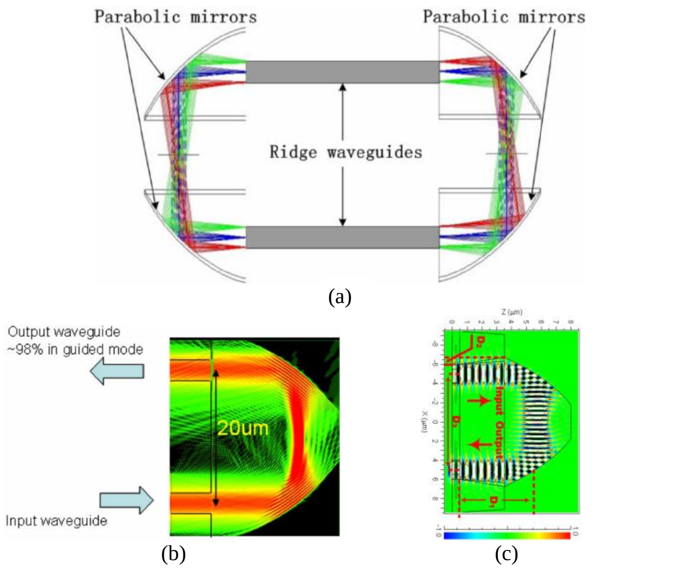

Fig. 1. (a) Design of parabolic mirror RR ring cavity, (b) FDTD simulation of the 20 μm RR, and (c) FDTD simulation of the 10μm RR.

Using parabolas with the waveguide ends on their focal plane as a starting structure, the mirror shape and positions in the RR are optimized by a ray tracing method to maximize the power transmitted via the RR between two parallel waveguides. This is necessary because pure parabolic mirrors only work for far-field while in our case the distance from end of waveguide to mirror is only 10 μm, which is comparable to the 2 μm width of the waveguide therefore cannot use the far-field assumption. Optimisation is achieved by the introduction of higher order aspheric terms into the mirror shape. The resulting mirror shape is verified with finite-difference time-domain (FDTD) simulation, which shows a 98% tansmission between the input and output waveguide modes (Fig. 1(b)).

The 20 μm distance between the waveguides limits the SRL device to a minimum of L=80 μm circumference even if the RWG length is reduced to zero. In practice the smallest devices that can be fabricated is about L=100 μm (equivalent to a R_{eq}=16 μm radius circular cavity) as some length of RWG

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is needed to form the output coupler. To further miniaturise the device, the distance between the two RWGs is reduced to 10μm. This would enable a minimum device size of 40 μm circumference (R_{eq}=6.4 μm). The mirror shape was modified and optimized again. The method of including higher order aspheric terms into to the pure parabolic curve used in the previous ray-tracing design has proven to be robust to for the even closer distance of 5 μm between the waveguide end and the mirror. This design again is verified by the finite difference time domain (FDTD) method (Fig.1 (c)). There is a futher trade-off in this even more compact design. The mirror width needs to be shortened because the access s-bend waveguides cannot be curved out too rapidly to prevent significant bending loss from occurring here, Therefore, the extension value D_2 has to be carefully chosen. When D_2 equals to 0.75μm, the transfer power ratio η defined as the output power over input power is ~96.5%, which is slightly smaller than 98% in the previous design.

III. Device Overall Design and Fabrication

All devices are fabricated on the same 5 strained InGaAlAs quantum well wafer emitting at 1550nm. The fabrication involves two different etch depth – shallow etch for the RWG and a 3.5μm deep high quality vertical etching step for the mirrors. Both etching steps are carried out using an Oxford Instrument ICP180 system. The structures achieved after the deep etching are shown in Fig.2(a) and (c).

For the 20 μm RR design (fig.2(a)), the overall device sizes implemented include circumference from 360 to 100 μm, or equivalent to circular radius of R_{eq}=50 to 16 μm. A typical L-I curve is shown in Fig.2(b) for a R_{eq}=25 mm device with 2 directional couplers and 4 output ports. Directional bistability is clearly defined above 80 mA. To achieve the smallest (R_{eq}=16 mm) devices, the directional couplers are terminated as shown in Fig.2(c), where only half the coupler length is used. The bistability in the L-I curve of fig.2(d) is not as clear-cut due to higher back-scattering in this design.

For the 10μm RR design, the main purpose at present is to achieve lasing in order to proof the design. Therefore devices of a relatively large circumference of R_{eq} of 38μm and 70μm are fabricated. The finished device is shown in Fig.2(e) and the L-I curves are shown in (f). The higher thresholds indicate that while lasing is achieved, the loss is higher than the larger RR structure, believed to be due to the extremely tight fabrication tolerance required for this design is barely achievable with the UV photolithography that we used.

I. Conclusion

Novel retro-reflector (RR) based semiconductor ring lasers have been designed to enable very small devices with potentially low threshold, good bistability, and ease of output coupling. Fabricated devcies successfully operated CW at room temperature. For RR width of 20μm, low threshold operation and clear-cut bistability has been achieved, and the smaller 10μm wide RR is also confirmed to be a viable design for even smaller devices to be fabricated. Future devices using e-beam lithography are being fabricated which should provide much better precision and therefore device performance for devices sizes of R_{eq}<10μm.

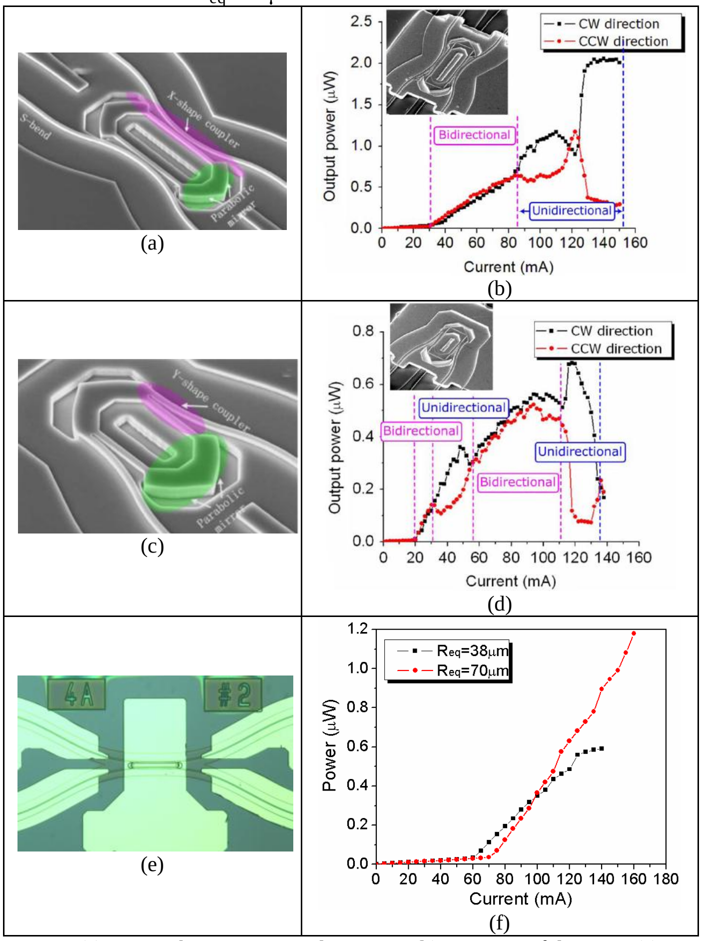

Fig. 2. (a) SRL with 20 mm RR and 4 ouputs, (b) L-I curve of device in (a) (c) SRL with 20 mm RR and 2 ouputs, (d) L-I curve of device in (c), (e)

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