Chirped Grating Annular Bragg Resonator Lasers: Manipulating Laser Beams in a 2-D Cylindrical Geometry

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The circular optical resonators have been studied since the late 1960's and the idea of applying the radial distributed feedback mechanism by circular grating to surface emitting lasers was first proposed in 1988 [1]. Since then, people have realized the optically pumped circular grating surface-emitting DFB lasers [2] and electrically pumped circular grating DBR lasers [3]. A judicious design of the circular gratings can guarantee a complete in-plane feedback so as to strongly localize the light in the prescribed region. Meanwhile, the annular Bragg walls also serve as an output-coupler to diffract the light out of the plane via first-order diffraction, producing a cylindrically symmetric surface-emitted laser beam with narrow divergence (see Figure 1). In the previous researchers' work, however, they employed the constant period gratings to provide the feedback, which seemed to directly follow the case in commercial 1-D DFB lasers. In fact, in the 2-D cylindrical case, the propagating waves in a cavity naturally turns to be the radial outward and inward cylindrical waves, mathematically represented by the first and second kinds of Hankel functions. The amplitudes of those waves decay with the radius (inversely proportional to the square root of radius ρ). More importantly, the period of those cylindrical waves shrinks for increased radius, leading to a set of positions of the Bragg walls different from that of commercial DFB lasers (see Figure 2). So starting from 2002, our group has been studying the "chirped grating" annular Bragg resonators (ABRs) and their applications in laser emission. Those devices were especially designed to confine the light in a central disk or a radial defect ring region by the Bragg reflection. The theoretical analysis and experimental realization were carried out [4,5].

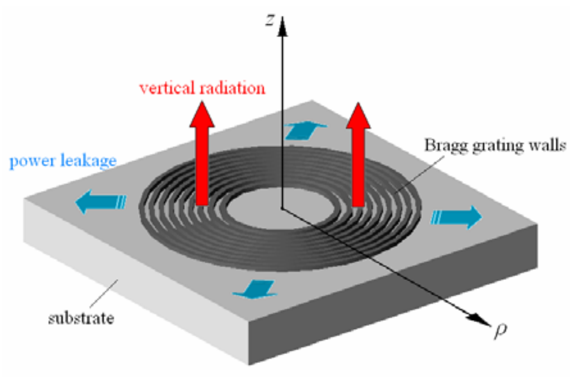

Figure 1. Schematic of a surface-emitting ABR laser

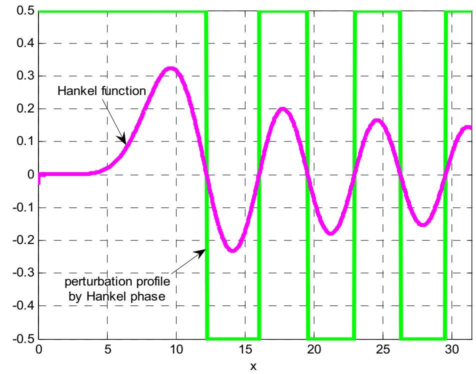

Figure 2. An illustration of the real part of Hankel function $H_m^{(1)}(x)$ (m=8) and the grating profile determined by its phase

Even though the theoretic framework had been already established and the experimental results of such ABR lasers seemed to agree with the theory quite well, the analysis was based on first-order coupled mode theory and applied to only passive devices. So there should be still room in further reducing the laser threshold by improving the structure design. In fact, a more systematic way by considering the radiated field within second-order coupled mode theory can help us understand more of the lasing properties of such resonators and hence reach that goal. Driven by that concern, we derived the coupled mode equations for second-order gratings in 3-D cylindrical coordinates with the consideration of vertical radiated field, and applied them to the configuration of disk ABR lasers, obtaining the characteristic equation, based on which we got the threshold gain and the resonance frequency detuning factor. Meanwhile, analyzing from the power loss mechanisms, we found the direct relation between the total optical loss and the threshold gain, which actually offers a powerful theoretical foundation for optimally designing the device parameters. By reducing the threshold gain while maximizing the ratio of "useful signal" to power leakage for the first lasing mode, we could get the optimum design of the surface emitting disk ABR lasers with predicted threshold gain one order of magnitude lower than that of normal radial DFB lasers (see Figure 3)[6].

On the other hand, the ABR structures mentioned above feed the whispering gallery modes (WGMs). Those modes representing the traveling waves propagate in the angular direction around the resonator within the prescribed region. To further lower the lasing threshold, an idea of ultra-localization of light by eliminating the WGMs was proposed. Given an angular perturbation within the otherwise WGM propagating regions, the angularly propagating waves would be further localized within the azimuthal defect due to the angular feedback mechanism. By confining light to a smaller area compared to the traditional Bragg resonators, the quality factor is expected to increase and consequently, the lasing threshold deceases. Meanwhile, this kind of ultra-compact angularly perturbed

ABR lasers can produce various beam patterns, which can meet the demands of the progress in some areas like optical tweezers, ultra-high-density optical memory and micro-fluidics. We have developed the analytical solutions by coupled mode theory for the coexistent radial and azimuthal perturbation (see Figure 4). Now we are still working on optimally designing the specific perturbation profiles to meet the needs in various occasions and experimentally realize them.

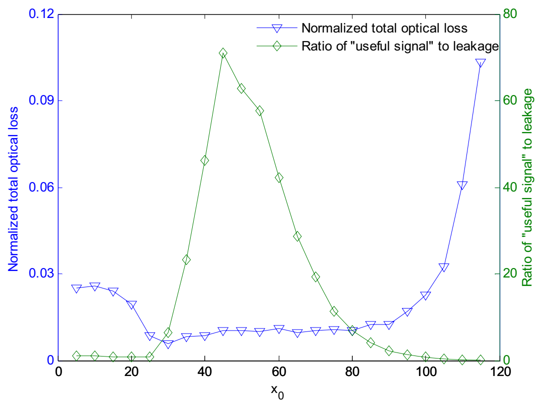

Figure 3. The total optical losses and the ratios of surface-emitted power to periphery power leakage of the first lasing modes of the disk ABR lasers with different inner radii x_0

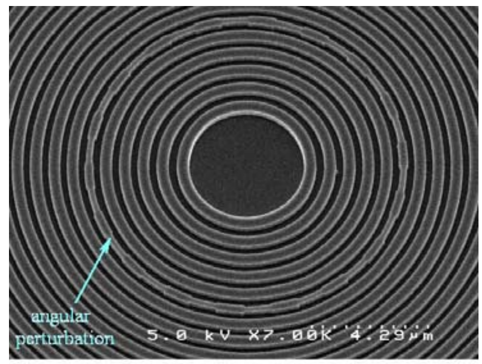

Figure 4. A SEM picture of a disk ABR laser containing both radial and angular perturbations

As the fabrication and material processing technologies have matured, people are able to make high-finesse micro-fabricated structures, enabling the realization of chirped Bragg grating to efficiently localize light in very small volumes. This new kind of surface emitting lasers are superior to their counterparts edge-emitting lasers in that they are inherently easier to realize the in-plane dense laser arrays and hence facilitate highly integrated optical circuits on a single chip. Their versatile grating designs also provide a way to manipulate the laser beams in a cylindrical geometry.

References:

[1] R. M. Shimpe, U.S. Patent 4 743 083 (1988)

[2] C. Wu, M. Svilans, M. Fallahi, T. Makino, J. Glinski, C. Maritan, and C. Blaauw, Optical Pumped Surface-Emitting DFB GaInAsP/InP Lasers with Circular Grating, *Electron. Lett.*, Vol. 27, No. 20, pp. 1819-1821, Sep. 1991

[3] C. Wu, M. Svilans, M. Fallahi, I. Templeton, T. Makino, J. Glinski, R. Maciejko, S. I. Najafi, C. Maritan, C. Blaauw and G. Knight, Room Temperature Operation of Electrically Pumped Surface-Emitting Circular Grating DFB Laser, *Electron. Lett.*, Vol. 28, No. 11, pp. 1037-1039, May 1992

[4] J. Scheuer and A. Yariv, Coupled-Waves Approach to the Design and Analysis of Bragg and Photonic Crystal Annual Resonators, *IEEE J. Quantum Electron.*, Vol. 39, No. 12, pp. 1555-1562, Dec. 2003

[5] J. Scheuer, W. M.J. Green and A. Yariv, Annular Bragg Resonators: Beyond the limits of Total Internal Reflection, *Photonics Spectra*, Vol. 39, No. 5, pp. 64-78, May 2005

[6] X. Sun, J. Scheuer and A. Yariv, to be submitted

Xiankai Sun’s brief bio:

Xiankai Sun was born in Wuhan, China in 1982. He earned his B.S. degree in physics from the University of Science and Technology of China, Hefei, China in 2004 and his M.S. degree in applied physics from the California Institute of Technology in 2006. His undergrad research focused on the growth, characterization, and device fabrication of ZnO thin films. Starting from fall 2006, he will be a third-year grad student in department of applied physics at Caltech. Now he is working in the Optical and Quantum Electronics Laboratory under guidance of Prof. Amnon Yariv. His research interests include theoretical analysis and experimental realization of the annular Bragg grating resonator lasers, microgear resonators and other nano-photonic devices.