Visualization of spatial structure of optical modes in half-disk lasers

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Abstract. The modal structure of half-disk lasers emitting in the middle IR-range was investigated. Scanning probe microscopy was used to map the intensity of optical radiation on the cleavage planes of half-disk lasers. The stability of optical modes in a half-disk lasers was studied by the geometric optics method of Poincare surface of section. It is shown that the deviation of the cleavage plane from the center of the disk leads to a rapid decrease in the number of stable spatial modes.

1. Introduction.

It is well known, that the high Q-factor of whispering gallery mode (WGM) disk lasers [1] (Figure 1a) provides relatively low current threshold values for laser emission. However, one of the main problems of these round-shaped lasers is the non-directionality of laser emission output. One of the approaches to improve directionality of WGM-lasers is the fabrication of half-disk resonators by cleaving the disk to two halves. Based on symmetry considerations, it is reasonable to assume that in an ideally split half-disk, the spatial structure of optical modes should be identical to that of the whole disk [2]. So, the areas of the most intense outcoming optical radiation must be at the very edge of the half-disk (Figure 1b). However, when splitting a disk, the cleavage plane does not pass exactly through the center (in this case it forms segment shaped resonator), which should lead to a perturbation of the spatial structure of optical modes (Figure 1c). The aim of this work was to study the spatial structure of optical modes in such segment shaped resonators. It is worth noting that this problem has not been previously studied in detail.

Recently, the authors of this work discovered the effect of a shift in the resonant frequency $\Delta\omega$ of an atomic force microscope (AFM) probe when it is illuminated [3]. This effect is due to the heating of the probe when the light is absorbed. In this case, the magnitude of the frequency shift is linearly proportional to the intensity of the light incident on the probe $\Delta\omega \sim I$. The model of light absorption related heating of the AFM-probe has been developed, which gives a satisfactory agreement with the experimental results [4]. It should be noted that in the paper [4] the absorption in traditional Si and Si₃N₄ AFM probes was calculated and it was shown that: 1) IR radiation is mainly absorbed in the upper metallization layer of the cantilever, 2) the absorption is significantly enhanced due to multiple
light reflections in the "cantilever-surface" optical cavity, 3) heating by radiation can be enhanced by using cantilevers with a small cross-section and with low thermal conductivity, which slows the heat sink from the heated part of the cantilever, 4) the characteristic heating temperature of standard cantilevers by infrared radiation ($P \approx 1$ mW) is from fractions of Kelvin degrees to several Kelvin degrees. Based on this effect, a new probe method was developed to measure light-induced frequency shifts (LIFS) for the near-field mapping of the intensity distribution $J(x, y)$ of the radiation of semiconductor laser structures (see Figure 1d) [3].

![Figure 1](image1.png)

Figure 1. (a) – Scheme of WGM-modes in the disk-laser (b) - Scheme of WGM-modes in the half-disk laser, (c) - Scheme of unevenly chipped segment shaped laser, (d) – Scheme of light detection by AFM on the cleavage of half-disk laser.

2. Results and discussion.
By the above-mentioned LIFS method the near-field measurements were made on the cleavages of infrared ($\lambda = 2.1 \text{mkm}$) half-disk lasers (GaSb/GaAlSbAs/GaInSbAs) [3]. It was found that when the pump current exceeds the threshold value ($I > I_{th}$) the complex series of light-emitting spots (symmetric with respect to the center of the dissected disk) appear on the surface at some distance from the edges of the disk (see Figure 2).

![Figure 2](image2.png)

Figure 2. LIFS images $J(x, y)$ measured near the edge of the half-disk laser obtained at different z-distances: (a) – 100nm, (b) – 400nm, (c) – 700nm, (d) – 1000 nm.
Figure 2 shows four LIFS images $J(x,y)$ obtained near the edge of the half-disk and measured with different probe-surface $z$-distances (50 nm, 400 nm, 700 nm, 1000 nm). It can be seen that the intensity of a number of spots rapidly decreases with $z$-distance, that is, these spots have an evanescent nature. With an increase in the probe-surface distance up to 1000 nm, only the light emission region with a diameter of about 4 microns can be seen and this is the light that propagates as traveling waves and can be detected by an IR optical microscope. A number of half-disk lasers with diameters ranging from 100 microns to 300 microns were studied in a similar manner. For these structures, it has been experimentally found that the regions of maximum intensity of the modes that emit light are “moved away” from the edge of the half-disk by a significant distance $\sim 30-50\lambda_m$ ($\lambda_m$ - wavelength in a medium), which differs significantly from the case of the whole WGM-disk. In addition, it was found that the spatial position of the emitting spots differs significantly for half-discs chopped with different small deviations ($\delta/R \sim 1-20\%$) from the center of the disk. Also, it was possible to observe a series of evanescent spots, which makes it possible to obtain information about "sealed" modes that experience total internal reflection inside the laser cavity and do not emerge outward in the form of traveling waves.

Within the framework of geometric optics, it is possible to explain the observed phenomena. To describe the beams of closed (and unclosed) ray trajectories, we used the PSOS (Poincare surface of section) diagram method [5]. The PSOS-diagrams are constructed in the following way: (i) the optical ray is launched into the resonator and the following are then monitored: (ii) the positions of the points on the resonator boundary in which the ray undergoes reflections $s_i$ (see Figure 3c), and (iii) the angles of reflection from the resonator boundaries $\theta_i$ (see Figure 3c). Then, for the whole set of rays in the resonator, a diagram is constructed in the coordinates ($s$; $\theta$) – this is the PSOS-diagram. Stable trajectories in the PSOS-diagram will correspond to closed figures, and unstable trajectories will correspond to the "dust" of random points. Using the PSOS-diagram method, it is possible to determine in the 2D resonator the presence of stable modes and the so-called "chaotic" modes [6]. "Chaotic" modes correspond to trajectories of rays that do not close and move randomly in the resonator.

![PSOS-diagram of a half-disk cavity resonator cleaved with a 20% deviation from the center and (b) - Stable “sealed” mode (half of the triangle, $m=3$), corresponding to the green area in PSOS-diagram; (c) - Stable “emitting” mode (half of the rectangle, $m=4$), corresponding to the red area in PSOS-diagram.](image-url)
It was observed, that with an increase in the $\delta/R$ deviation parameter (where $\delta$ is the deviation from the center of the half-disk) the portion of the "chaotic sea" in the PSOS diagram grows and only a small number of stable spatial modes remain (see Figure 3). It is also worth noting that as the deviation $\delta/R$ increases, the "chaotic sea" primarily devours those modes that have been located near the edge, and only modes that have been moved away from the edge remain stable. This important result qualitatively allows us to explain why the emission areas in unevenly chipped half-discs are moved away from the edge. The second important result that can be obtained by analyzing PSOS-diagrams is the presence of two categories among stable modes: (i) total internal reflection (TIR) modes, which correspond to closed ray trajectories that fall on all boundaries of resonator at angles greater than the TIR-angle and (ii) NonTIR-modes, which correspond to closed ray trajectories that fall on certain regions of the resonator boundaries at angles smaller than the TIR-angle. On the PSOS diagrams TIR-modes corresponds to "figures" entirely placed above the TIR-angle $\theta_{\text{TIR}}=\arcsin(1/n)$, while NonTIR-modes correspond to figures located below the TIR-angle. It should be noted, that TIR-modes have a high Q-factor, they are "sealed" inside the resonator and cannot emit light outward in the form of a traveling wave. Outside the resonator, the TIR-modes can only appear in the form of exponentially decaying evanescent waves. On the other hand, Non-TIR modes can emit light outside of the resonator in the form of a traveling wave and this light can be detected by "far-field" optical microscopes.

It should be noted also, that the analysis of PSOS-diagrams makes it possible to estimate the angular divergence of the light beam emerging from the resonator [5]. In the simplest case, this can be done as follows: 1) one should choose a stable NON-TIR mode that contains an "island" located in the PSOS-diagram below the critical TIR-angle, 2) then the angular divergence of this beam inside the resonator is determined $\theta_{\text{max}}-\theta_{\text{min}}$ (in the PSOS-diagram, this is simply the size of an "island" along the vertical axis of the incident angles $\theta$), 3) then this value can be multiplied by the refractive index of the resonator (n), thus obtaining the angular divergence of the light beam emerging from the resonator. In segment-shaped resonators by changing the parameter $\delta$ the portion of the chaotic sea can be increased, thus reducing the size of stable modes "islands" on the PSOS-diagram. This reduces the angular divergence of the light beams and improves directionality of laser emission output.

Thus, analysis of PSOS-diagrams allows to determine the location of the regions of light emission and angular divergence of the emerging light beams for half-discs cleaved with a small deviation $\delta$ from the center. The presence of two effects: (i) the absorption by the "chaotic sea" of the modes located near the half-disc edge and (ii) the presence among the surviving stable modes of the nonradiating TIR-modes allows to explain why the light emission areas in unevenly cleaved discs are moved away from the edge.

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