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OPTICAL RESONATORS AND THEIR TYPES

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Abstract: Optical resonators are fundamental components in modern photonics and laser systems, designed to confine and sustain electromagnetic waves through repeated reflection or interference. They play a critical role in determining the spectral, spatial, and temporal properties of optical radiation. This article provides an overview of optical resonators, explaining their basic operating principles and key physical characteristics such as resonance conditions, quality factor, and mode structure. Various types of optical resonators are discussed, including Fabry–Pérot resonators, ring resonators, whispering gallery mode resonators, photonic crystal resonators, and fiber-based resonators. Each type is analyzed in terms of its structure, advantages, limitations, and typical applications. The article highlights the importance of resonator design in fields such as laser technology, optical communication, sensing, and integrated photonics. Understanding the different types of optical resonators and their properties is essential for the development of efficient and high-performance optical devices.

Keywords: Optical resonators, Fabry–Pérot resonator, ring resonator, whispering gallery modes, photonic crystal resonator, fiber optical resonator, laser systems, photonics.

When the Fabry-Perot interferometer is used as a resonator in optical quantum generators, it is possible to obtain directed coherent laser radiation. In addition to the Fabry-Perot interferometer with a flat parallel surface, interferometers with a spherical and parabolic surface are also used in optical resonators. From a theoretical point of view, an electromagnetic wave in a laser resonator can be imagined as a system of several functions depending on three indices, divided into a series. Each of them is associated with a certain type of wave oscillations, denoted by. The first two indices under capital letters denote the transverse structure of the electromagnetic field (transverse oscillating wave) - For each transverse wave, several longitudinal waves correspond. These waves differ from each other by the number of waves (half-waves) that can be located along the length of the resonator. These oscillations are denoted by the q-index. Each type of oscillation has its own frequency, which is determined by the division.

The mode of longitudinal waves participating in the generator and its resonator is determined by the width of the luminescence line of the active element and the resonator in lasers. There are many monographs and reviews on this subject. Below we will consider the factors that determine the transverse and longitudinal structure of the electromagnetic field in the resonator. The structure of transverse vibrations is due to the diffraction of radiation. It is associated with diffraction losses in elements that limit the radiation aperture and occur as a result of reflection from mirrors and surfaces. The distribution of electromagnetic field waves in an optical resonator was first studied by Huygens-Fresnel.

If we assume that the dimensions of the mirror are very large compared to the wavelength, the electromagnetic field in the resonator is very close to the transverse position and is polarized in one plane, then the area illuminated by the slit is determined by the surface integral in the Fresnel zone. Where the area in the slit k is the scattering constant in the medium; R is the distance from the slit to the observation point; X is the angle between the normal to the surface of the slit and the radius vector. The value of the losses for vibrations of different orders depends on the Fresnel number and has the following form: Here are gamma functions. The diameter of the radiation on the surface of the mirrors inside the confocal resonator is small and does not depend on the dimensions of the mirrors: . This situation leads to the fact that confocal resonators are rarely used in practice, since the utilization factor of the resonator active element is not high in such resonators. In flat-surface mirror resonators, the radiation surface is close to the size of the mirror surface, therefore, in resonators with flat mirror surfaces, the volume of the active element is fully used. The phase shift and losses for vibrations of different orders are determined as follows.

Here is the zero of the n-th order Bessel function. This formula cannot be applied to cases with small values of the Fresnel number and low losses, as in confocal resonators. Flat mirror resonators are simple in structure and are convenient to use in cases where the number of oscillations is not important. In addition, in flat parallel mirror resonators, certain types of oscillations are isolated, which occupy a larger useful volume than in other resonators. This, in turn, increases the efficiency of the inverse medium.

Unsteady resonators. The steady-state resonators considered above can be converted to unstable resonators by changing the distance between their mirrors in the steady state limit or by increasing the radius of curvature of the mirrors. In this case, to extract radiation from the unstable resonator, one of the reflecting mirrors of the resonator is made semi-transparent. For unstable resonators, diffraction losses increase rapidly for all types of oscillations. Resonators with large diffraction losses are also of interest. This situation makes it possible to remove radiation from the resonator in the form of a ring. In this case, the surface of the radiation, which has been reflected several times from the reflecting mirrors, expands and on the last return reaches such a size that its dimensions exceed the diameter of one of the reflecting mirrors of the resonator and leaves the resonator. The exit of radiation from the resonator along such a ring-shaped path is also called a diffraction path.

In unstable resonators, the value of the average energy loss of low-type modes in a first geometric approximation compared to stable resonators (independent of the dimensions of the mirror and the shape of the mirror) when returning from the mirror once is determined as follows.

To obtain the second harmonic, a nonlinear crystal is placed inside the laser resonator. One mirror of this resonator has the property of reflecting the fundamental radiation 100%, and the second mirror completely transmits the second harmonic radiation. In this case, all the second harmonic radiation is removed from the resonator. The rate equations written for the free generation mode determine the dependence of the output power of the second harmonic radiation on the generator parameters (internal loss coefficient, decay rate, luminescence time, total number of active particles, etc.). The presence of nonlinear elements inside the resonator not only leads to the receipt of the second harmonic, but also changes the pulse shape. The nonlinear dependence of the losses inside the resonator on the power of the fundamental radiation. causes internal negative feedback. The linear dependence of the F.I.K. on the laser power leads to the fact that the losses in the resonator are not large when receiving the second harmonic. The ratio of the relative density of photons to the inverse state is as follows:

Where is the ratio of the photon density and the magnitude of the inverse state to the density of active particles; the relative inverse state of the photon density in the resonator without the radiation being converted into the second harmonic. The appearance of a unit of time (the time during which photons pass through the resonator once) is taken into account from the moment of turning on the resonator. At the initial time, the photon density is determined by the spontaneous emission, which is small.

Conclusion: In conclusion, optical resonators are essential elements in a wide range of optical and photonic systems, as they enable the confinement and control of light with high precision. Different types of optical resonators, including Fabry–Pérot, ring, whispering gallery mode, photonic crystal, and fiber-based resonators, offer unique properties that make them suitable for specific applications. The choice of resonator type significantly influences the performance of optical devices, particularly in terms of efficiency, stability, and spectral characteristics. Advances in resonator design and fabrication continue to drive progress in laser technology, optical communications, and sensing applications. A thorough understanding of optical resonators and their operating principles is therefore crucial for the development of next-generation photonic technologies.

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