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Vertically emitting silicon disk resonators with periodic shape modulation

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ABSTRACT

It is shown by direct numerical modeling, using the 3D FDTD method, that a disk resonator with a sinusoidal modulation of its boundary has not only a modified frequency spectrum, but also a greater proportion of its optical radiation is directed normal to its surface. Simulations are carried out for a set of disk resonators on a typical silicon-on-insulator structure with a 250-nm silicon core and a disk diameter of about 2.6 μm with the 5% sinusoidal boundary perturbation. Depending on the optical wavelength, the far-field radiation pattern looks either like a quasihomogeneous optical beam or a torus, having a maximum or minimum intensity at its center, respectively.

1. Introduction

Silicon photonics [1,2] is among the modern technologies forming the backbone of today's information infrastructure. One of the most important problems that remains to be resolved is the creation of a completely silicon optical light source [3,4]. There is no direct optical transition under normal conditions in silicon. Therefore, special technologies should be developed to support free charge carrier radiative recombination. This can be realized by creating defect centers [5] or quantum dots [6,7] that construct semiconductor impurity zones. Based on this, it is possible to construct silicon optical radiation emitters [4,6] that operate in the near-IR range, making them usable in telecommunication and optical interconnection systems.

Unfortunately, the volume concentration of radiant centers is not high in silicon structures; therefore, to increase radiation efficiency, it is necessary to use high-Q resonators based on photonic crystals [6]. The active area of a photonic crystal has submicron sizes and the observable optical radiation power appears to be rather low. For radiant energy magnification, it is possible to increase the number of used nodes in the photonic crystal resonator [7] or to integrate a system of single resonators into a phased array of coupled emitters [8,9], that can generate radiation in the surface normal direction, as a microbeam. The active area size can also be increased by using a disk resonator [7,10]. It is known that the disk resonator radiates mainly in the plane of a structure [11]. Therefore, for energy output efficiency magnification, it is necessary to couple the disk to a neighboring optical waveguide [12,13].

In order to generate efficient optical radiation, from the silicon disk resonator, in a surface normal direction, we modulate the disk shape with a sinusoidal curvature of its side boundary. Note that, in the scientific literature, disk resonators with microgear-shaped modulation [14] or disks with a sinusoidal boundary [15] have already been described. In particular, it was shown that the periodic curvature of the boundary essentially changes the frequency spectrum of such resonators and makes it possible to achieve a condition at which efficient laser generation occurs for the modes which have an angular period (azimuthal number) that is close to the number of modulation periods (M) of the disk boundary.

Disk and ring resonators with the periodic shape modulation have proven to be useful for creating laser structures. Unfortunately, the boundary shape influence on the change of the far-field radiation spectrum has not been considered in the majority of

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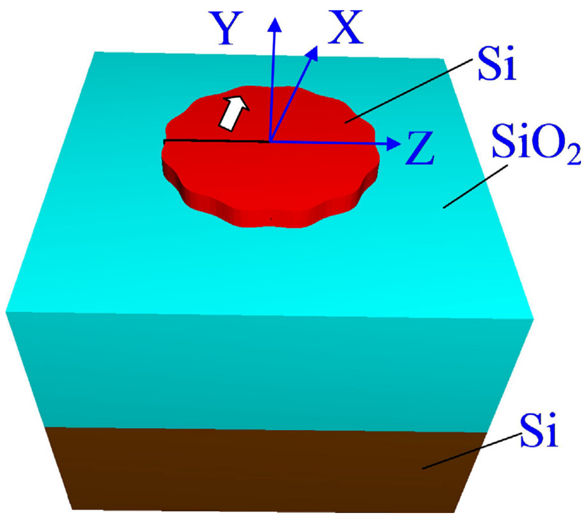

Fig. 1. General structural view of the optical resonator with the periodic shape modulation.

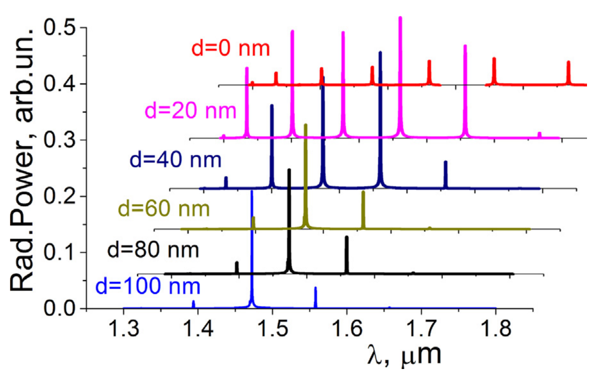

Fig. 2. Evaluation of the spectrum of the upwards radiated power normal to the surface for different modulation amplitude *d*.

investigations. At the same time, it was shown in the research of terahertz quantum cascade disk lasers that using a microgear-shaped metal electrode with a 16-period grating [16] makes it possible to increase, the radiation intensity (up to nearly 20%) 50 times along the surface normal. If the azimuthal number of a mode coincides with the number of fingers on the electrode (equal to 17 for a disk with diameter 184 μm), the far-field laser emission patterns, at the frequency of 3.3 THz, will have a torus-shaped structure [16] with an intensity dip in the central part of the pattern.

Our analysis shows that a similar effect can be observed in optical disk resonators with the periodic side boundary shape modulation. We show that there is a condition at which the given disk resonator radiates efficiently in a direction normal to its surface, and that there is a possibility of quasihomogeneous optical beam generation, which is important for a number of practical applications.

2. Results and discussion

We numerically study a disk resonator (see Fig. 1) on the standard waveguide silicon-on-insulator (SOI) structure, in which a thin 250-nanometer silicon layer is located on the 2.0 μm thick buffer oxide layer. The resonator boundary has a periodic sinusoidal curvature with an amplitude *d* of about 3%, related to its diameter *D*. The structure parameters ($M = 12$ and $D = 2.6$ μm) are optimized for operation at a telecom wavelength of about 1.56 μm.

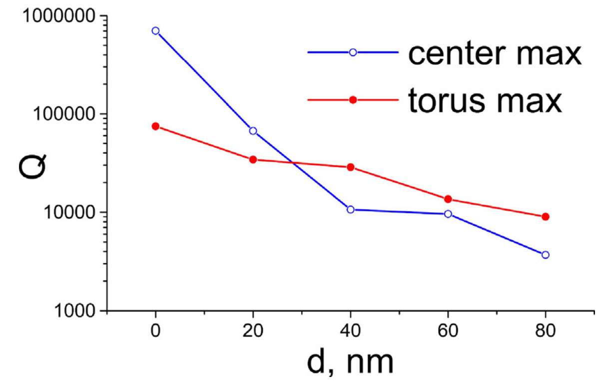

Fig. 3. Quality factor as a function of the modulation amplitude *d* for the two strongest spectral components corresponding the normal radiation having the maximum and minimum (torus like) far field.

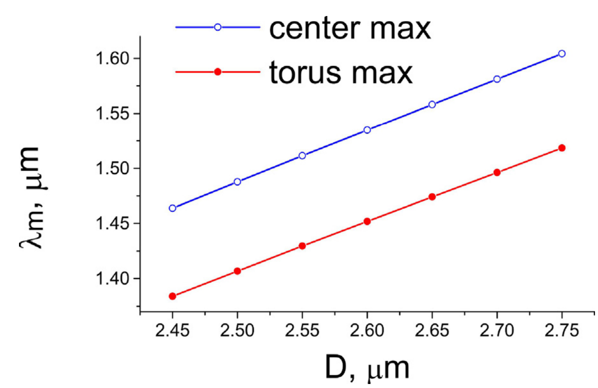

Fig. 4. Optical wavelength corresponding to different far-field patterns as a function of disk diameter *D*.

The quantitative analysis of optical disk resonator properties is accomplished by the direct three-dimensional (3D) numerical modeling using the finite difference time domain (FDTD) method. The commercial FDTD software available from Rsoft/Synopsys [17] was used in the present work, as it proved to be efficient for similar tasks [18]. The simulation grids of 50 and 40 nanometers are used in the vertical and horizontal directions of the structure, respectively. The comparative analysis of disk resonators with a different curvature amplitude of its periodic boundary shows that the presence of periodic resonator boundary modulation essentially modifies the frequency spectrum. Namely, increasing the curvature amplitude *d*, one can transform the radiated spectrum from the case of simultaneous excitation of multiple wavelength, different corresponding modes supported by the unperturbed disk resonator ($d = 0$ nm), to the case when only two main components survive (see Fig. 2). This periodic corruption of the disk boundary also worsens the quality factor (see Fig. 3), which we determine from the time power decay of the appropriate modes excited in the structure.

We are interested in the light scattering out of the disk plate that could be caused by the periodic grating on the boundary. We have examined a set of photonic disks with the periodic shape modulation at different structure parameters *d*, *M* and *D* and found that the best normal radiation takes place for the particular values of *M* equal to 12 and *D* equal to 2.6 μm. By a small variation of disk diameter *D*, one can gradually control the resonance wavelengths (see Fig. 4) for the operation in the telecom range. The two strongest spectral components for the moderate curve amplitude $d = 80$ nm correspond to the mode of the disk resonator with azimuth number $m = M$ and $m = M-1$. They provide the light scattering by the periodic surface corruption – both normal to the surface (upward and downward) and in the structure plate (in *X* and *Z* directions).