Research Article

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Free-space-coupled wavelength-scale disk resonators

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Abstract: Optical microresonators with low quality factor (Q) can be efficiently excited by and scatter freely propagating optical waves, but those with high Q typically cannot. Here, we present a universal model for resonators interacting with freely propagating waves and show that the stored energy of a resonator excited by a plane wave is proportional to the product of its Q and directivity. Guided by this result, we devise a microdisk with periodic protrusions in its circumference that couples efficiently to normally incident plane waves. We experimentally demonstrate several microdisk designs, including one with a radius of 0.75 λ0 and Q of 15,000. Our observation of thermally-induced bistability in this resonator at input powers as low as 0.7 mW confirms strong excitation. Their small footprints and mode volumes and the simplicity of their excitation and fabrication make wavelength-scale, free-space-coupled microdisks attractive for sensing, enhancing emission and nonlinearity, and as micro-laser cavities.

Keywords: flat optics; free space coupling; microresonators.

1 Introduction

Optical microresonators are one of the main building blocks of photonic integrated circuits [1, 2], lasers [3], and flat optical elements [4–6]. Waveguide-coupled on-chip microresonators such as microtoroid [7], microring, microdisk, and 1D and 2D photonic crystal resonators are used as filters [8, 9], sensors [10, 11], laser cavities [12], and for the enhancement of light–matter interaction [13], but they require coupling light to optical waveguides, which is an intricate and typically inefficient process. Free-space-coupled (FSC) optical resonators such as guided-mode resonators, vertical Fabry–Pérot resonators [14–16], and Mie resonators [17] can be readily excited and probed using free space excitations; however, they have larger footprints or lower quality factors (Q) than waveguide-coupled resonators. Although some high-Q on-chip resonators can be probed using free-space illumination [18], they can only be weakly excited, and a crossed-polarization scheme is used to detect the small amount of light scattered by the resonant mode.

Large and dense arrays of FSC resonators such as Mie or vertical Fabry–Pérot resonators with subwavelength footprints and low and moderate Qs form flat optical elements such as metalenses [4, 6]. However, higher Q Mie resonators, which use high-order resonance, cannot be efficiently excited using free-space excitations. High-Q vertical Fabry–Pérot resonators that use distributed Bragg reflectors [19], such as the ones used in vertical-cavity surface-emitting lasers, have significantly larger footprints and mode sizes, and their resonant wavelengths cannot be controlled using lithographic patterning. High Q and efficient free-space excitation are typical features of guided-mode resonances, also known as bound states in the continuum, but such resonant modes are not localized, and using a finite size resonator reduces their quality factors, thus limiting their minimum dimensions to tens of wavelengths [20–23]. Moreover, fabrication-induced non-uniformities cause further inhomogeneous broadening and reduction of their Qs.

Here we present the theory, design, and experimental demonstration of high-Q resonators with a small footprint and mode size that can be efficiently excited and probed using free-space illumination. The resonators are subwavelength and wavelength-scale microdisks that are modified by adding weak azimuthal gratings that enable efficient free-space coupling. Azimuthal gratings have been...
previously added to microdisks and microrings to selectively increase or decrease their radiation quality factors [24, 25], modify their dispersion and resonant wavelengths [26], generate beams carrying orbital angular momentums [27], selectively couple different degenerate resonant modes [28], and identify azimuthal orders of resonant modes [29, 30]. In contrast, the main purpose of the azimuthal grating in this work is to efficiently couple incident plane waves to a resonant mode. The fabrication of the FSC microdisks requires only one lithography step, and their resonant wavelengths can be controlled lithographically. Because of their small footprints and localized modes, large and dense non-interacting arrays of these resonators can be realized. In the following, we introduce a universal model for the excitation of FSC resonators by plane waves and more general free propagating waves, and we present the operation principle and details of the design, fabrication, and characterization of FSC microdisk resonators.

2 Results

Figure 1a schematically shows an arbitrary open resonator and the radiation pattern of its resonant mode. The mode has a resonant angular frequency \( \omega_0 \), a quality factor \( Q \), and its radiation mode’s directivity is \( D(\theta, \phi) \). We assume that the resonator is excited by a plane wave with an angular frequency \( \omega_0 \) and energy density \( u_i \). A coupled-mode equation that describes the dynamics of coupling between a high-\( Q \) open resonator and an incident wave is presented in Supplementary Note 1, and expressions for the stored energy and absorbed power are given in Supplementary Note 2. As it is shown in Supplementary Note 2, the energy stored in a resonator made of lossless materials that is excited by the plane wave is given by

\[
U_s = \frac{\mu \lambda_0^3}{2\hbar^2} QD,
\]

where \( \lambda_0 = \frac{c}{\omega_0} \) is the free-space resonant wavelength of the resonator, and \( c \) is the speed of light in a vacuum. The stored energy, which is an indicator of the excitation strength of the mode, is proportional to the product of \( Q \) and the directivity \( D \) of the resonators’ radiation pattern along the incident direction of the plane wave. Therefore, a resonator can be efficiently excited by a plane wave if its \( QD \) is large.

A microdisk resonator supports high-\( Q \) modes, but its radiation pattern vanishes in the direction normal to the plane of the disk. Figure 1b shows a 0.25-\( \mu \)m-thick amorphous silicon (a-Si, \( n = 3.6 \)) disk resonator with a diameter of 2.29 \( \mu \)m on a fused silica substrate. Figure 1b also shows the radiation pattern and the electric energy distribution of its resonant mode with a free-space wavelength of \( \lambda_0 = 1.53 \) \( \mu \)m computed using a commercial finite element solver [31]. The mode is quasi-transverse electric with a quality factor of \( Q = 8.6 \times 10^3 \), and its electric field radial component \( E_r \) is proportional to \( \cos N\phi \) for \( N = 10 \) (\( \phi \): azimuthal coordinate). The directivity of the radiation pattern of the mode in the direction normal to the plane of the disk is zero; thus, the mode cannot be excited by a normally incident plane wave.

The polarization current density of the mode \( \mathbf{J}_M^M = j\omega_0\varepsilon_0(\varepsilon_r - 1)E_M^M \) is the source of radiation and can be examined for an intuitive understanding of the mode’s radiation pattern (\( \varepsilon_0 \): free-space permittivity, \( \varepsilon_r \): spatially dependent relative permittivity of the resonator, \( E_M^M \): electric field of the resonant mode, and superscript M standing for “mode”). The directivity along any direction is proportional to the modulus squared of the projection of \( \mathbf{J}_M^M \) on the electric field of the incident wave [32]. The relative permittivity of the microdisk \( \varepsilon_r \) does not depend on \( \phi \), thus \( \mathbf{J}_M^M \) varies as \( \cos N\phi \), but the radial component of the electric field of an \( x \)-polarized plane wave normally incident on the microdisk varies as \( \cos \phi \). Therefore, the projection of \( \mathbf{J}_M^M \) on the incident electric field and the directivity along the normal direction are zero when \( N = 1 \). However, modifying \( \varepsilon_r \) by small amounts such that it contains terms that vary as \( \cos(N \pm 1)\phi \) while the electric field of the mode is not significantly perturbed will lead to terms in \( \mathbf{J}_M^M \) that vary as \( \cos \phi \) and thus nonzero directivity along the normal to the microdisk plane. Figure 1c shows a top view of the radial electric field of a resonant mode of a microdisk resonator with \( N = 5 \). Slightly modifying the resonator by adding \( N - 1 = 4 \) small perturbations around the microdisk (depicted by small circles in Figure 1c) will lead to a term in \( \mathbf{J}_M^M \) that varies as \( \cos \phi \) and can be considered an electric dipole in the microdisk plane. This dipole term couples to normally incident plane wave fields and effectively operates as a coupler between the plane wave and resonant mode of the microdisk.

The perturbations shown in Figure 1c form an azimuthal grating. Azimuthal gratings could be realized by adding periodic structures close to the microdisk, but to reduce the device footprint, we chose to modulate its radius instead. The azimuthal gratings considered here are created by modifying the disk radius as \( \rho = R_0 + d \sin m\phi \) for different values of \( d \), \( m \), and \( n \). The values of \( m \) and \( n \) were selected to have \( N - 1 \) or \( N + 1 \) grating periods around the microdisk circumference. The grating strength is a function of its maximum protrusion \( d \) and its duty cycle, which the latter is controlled by \( n \).

Figure 1d shows the resonant mode and the radiation pattern of the microdisk shown in Figure 1b after adding
$N + 1 = 11$ protrusions. The radiation pattern has large lobes normal to the plane of the microdisk. Figure 1e shows smaller microdisks supporting modes with $N = 5$ and 6 at $\lambda_0 = 1.53 \, \mu m$ and refractive index modifications with $N + 1$ periods around the microdisk circumference. These resonators also emit significantly normal to their planes and can be excited by normally incident plane waves. The simulations confirm that weak azimuthal gratings with $N \pm 1$ periods around the microdisk circumference lead to emission of the resonant mode in the direction normal to the microdisk. The azimuthal grating serves a similar purpose as an evanescently coupled waveguide, but instead of coupling the resonant mode to a guided mode, it couples it to freely propagating waves. As the grating...
strength increases, the coupler loads the resonator more, and its quality factor decreases, as shown in Figure 1f.

To confirm the excitation of the microdisk mode by normally incident plane waves and to quantify the effect of varying grating strengths, we found the energy stored in the microdisk when illuminated by a plane wave. Figure 2a shows a schematic of the simulated microdisk. The microdisk is the one shown in Figure 1d and is illuminated by a plane wave normally incident from the substrate. The energy stored inside the microdisk is normalized to the energy of the incident plane wave in a $\lambda_0^3$ volume and is shown as a function of the radius modulation $d$ in Figure 2b. As Figure 2b shows, the stored energy is enhanced significantly by the addition of the grating, indicating the excitation of the resonant mode, and there is an optimal value for the grating strength ($d = 30$ nm for this resonator) that maximizes the stored energy and mode excitation amplitude. As mentioned earlier, the stored energy is proportional to the product of the directivity and the quality factor. The directivity increases and the quality factor decreases with increasing $d$; thus, there is an optimal $d$ value, or coupling strength, that maximizes their product. This behavior resembles the critical coupling condition in evanescently coupled resonators. Figure 2c shows the normalized stored energy versus wavelength for $d = 30$ nm. The narrow, Lorentzian line shape and its large peak value indicate efficient excitation of the resonant mode.

The loaded $Q$ and the mode volume for this resonator are $Q = 4.33 \times 10^4$ and $V = 2.21 (4\pi R_0^2)^3$ that result in a Purcell emission enhancement factor of $F = \frac{2}{\lambda_0^3} \frac{V}{(1.145\mu m)^3} = 1489$. The large Purcell factor and the directive radiation pattern of this resonator (Figure 1d) make the FSC microdisks suitable for enhancing the rate of spontaneously emitted photons and efficiently collecting them.

To demonstrate the feasibility and performance of the FSC microdisk resonators, an array of microdisks were designed, fabricated, and characterized. Amorphous silicon microdisks with a thickness of $0.25$ µm and diameters between 1.4 and 2.3 µm, corresponding to $N$ values from 5 to 10, were designed for operation at $\lambda_0 = 1.53$ µm. The microdisks were fabricated by depositing a 0.25-µm-thick layer of hydrogenated a-Si on a fused silica substrate, electron beam lithography using a negative resist, and dry etching (Methods). Figure 3a shows the SEM images of three fabricated microdisks with $N = 5, 6, 10$ and $(d, m, n)$ values of $(90$ nm, $6, 1), (75$ nm, $7, 21)$, and $(30$ nm, $5.5, 100)$, respectively.

The microdisks were characterized by measuring their transmission spectrum using the setup shown in Figure 3b. The resonators were illuminated by focused polarized light from a tunable laser, and the transmitted light was collected using an objective lens and measured (Methods). Figure 3c shows an example of the measured spectrum for a microdisk with $N = 10$ (shown in Figure 3a). The transmission spectrum typically shows a peak at the resonant wavelength of the device. However, depending on the alignment of the objective lenses, Fano line shapes (Figure 3c inset) were also observed, which indicate interference between the light scattered by the microdisk resonant mode and unscattered light. For maximal excitation of the resonant mode, the numerical aperture of the excitation objective lens should be selected to match the angular divergence of the microdisk radiation pattern’s lobe along the excitation direction (Supplementary Note 1). However, we did not optimize the objective lens and used a single lens for measuring different microdisks.

Figure 2: Excitation of an FSC microdisk resonator by a plane wave. (a) Illustration of an FSC microdisk resonator excited by a normally incident plane wave. (b) Normalized stored energy $U_i/(u_i\lambda_0^3)$ as a function of the grating protrusion $d$ at its resonant wavelength, and (c) as a function wavelength for $d = 30$ nm. The boundary of the microdisk is defined in polar coordinates according to $\rho = R_0 + d (\sin m\phi)^n$, where $R_0 = 1.145$ µm, $m = 5.5$, and $n = 100$. 
A microdisk supports two degenerate resonant modes at each resonant wavelength, both with $N$ field oscillations around its circumference whose difference is a rotation by half of the oscillation period (i.e., by angle $\pi/N$). The addition of the azimuthal grating with $N \pm 1$ periods does not break their degeneracy, but their coupler dipole moments (Figure 1c) are rotated by 90°, and the two modes can be addressed independently using two orthogonal linear polarizations. Small and random variations in the microdisk radius created during the device fabrication remove the degeneracy of the two modes and split their resonant wavelengths [33]. Figure 3d shows two transmission spectra of a microdisk with $N = 10$ that are measured with two orthogonal linear polarizations. The splitting of the modes for this device is larger than the width of resonance peaks, and the two modes can be resolved.

The quality factors of the microdisks were determined by fitting Fano line shapes to the measured transmission spectra (see Methods). Figure 3e shows the quality factor of microdisks with $N = 10$ as a function of the protrusion depth $d$. As expected, the quality factor decreases with increasing $d$; however, the highest measured quality factor was $1.5 \times 10^4$ which is by a factor a few smaller than simulated values (Figure 1f). We attribute the reduction in $Q$ to absorption losses in a-Si and random radius variations and roughnesses of the fabricated microdisks. Replacing

Figure 3: Experimental results.
(a) Scanning electron micrographs of fabricated FSC microdisk resonators with different azimuthal orders $N$. (b) Simplified schematic of the setup used for measuring transmission spectra of the resonators. (c) An example of a transmission spectrum of an FSC microdisk resonator. The inset shows another example of the observed transmission spectrum. (d) Measured transmission spectra of a resonator for two perpendicular linear polarizations of incident light. (e) Measured quality factors of FSC microdisks as a function of the protrusion depth $d$. The schematic of the resonator is shown in the inset. (f) Simplified schematic of the setup used for measuring reflection spectrum of FSC resonators. (g) Reflection spectrum of the resonator whose transmission spectrum is presented in (c). (h) Transmission spectra of an FSC resonator measured at different optical powers. TLS: tunable laser source, PC: polarization controller, OL: objective lens, FC: fiber coupler, PD: photodetector.
a-Si with crystalline silicon should reduce some of these losses and increase $Q$.

The microdisks can also be probed by measuring their reflection spectra using the confocal setup shown in Figure 3f. Measuring the reflection spectrum is the preferred method for resonators fabricated on silicon-on-insulator (SOI) wafers. Figure 3g shows the reflection spectrum of the resonator, whose transmission spectrum is presented in Figure 3c. A reflection dip is observed at the resonant wavelength of the microdisk, which is consistent with the peak observed in the transmission spectrum. Many resonators may be probed in series in reflection mode using the setup shown in Fig. 3f, or in parallel by imaging the light reflected from the resonators while tuning the incident light’s wavelength.

To further verify the strong excitation of the resonant mode by free-space excitation, we measured the transmission spectrum of the microdisks at different incident optical powers. Thermally-induced optical nonlinearity, which is due to absorption losses in a-Si and its temperature-dependent refractive index, can be used as an indicator of the resonant mode’s excitation strength. Figure 3h shows the transmission spectra of a microdisk with $d = 80 \text{ nm}$, $m = 5.5$, and $n = 100$ obtained at different incident powers. Asymmetric line shapes, which are indicators of nonlinearities, were observed at sub-milliwatt incident power, and onsets of optical bistability (identified by the discontinuity in the measured transmission spectrum) as low as 0.7 mW were observed (Figure S1). The observation of optical nonlinearities at such low incident powers confirms the strong excitation of the resonant mode.

3 Discussion

The universal model we presented for the excitation of resonators by freely propagating waves describes the dynamic response of the resonator, provides simple relations for the accurate determination of stored energy and absorbed power, and enables the intuitive design of FSC resonators. FSC microdisk resonators with moderate and high $Q$ factors can be efficiently and readily excited and probed by free space illumination and collection (e.g., in a confocal arrangement). These resonators have subwavelength and wavelength-scale footprints enabling the realization of their dense arrays. Their small mode sizes and relatively high $Q$s lead to large enhancements of stored optical energies, nonlinearities, and emission rates (i.e., large Purcell factors), and their directional emission increases the collection efficiency. They can be fabricated using single-step lithography and a dry etch step. The devices presented here were implemented using a-Si on fused silica to enable the characterization of their transmission spectra. Similar resonators can be designed and implemented using SOI or silicon nitride on silicon dioxide platforms and achieve even higher $Q$ because of their smaller absorption losses. The small footprint and mode volume, simplicity of excitation and probing, moderate fabrication complexity, and the relatively high $Q$, make FSC microdisk resonators attractive for sensing, filtering, enhancing emission and nonlinearity, and as cavities for micro-lasers.

4 Methods

4.1 Design

An array of FSC microdisk resonators for six different azimuthal mode orders from $N = 5$ to 10 and for 17 different protrusion depths $d$ values from 20 to 100 nm in 5 nm steps were designed for the resonant wavelength of 1530 nm. The boundaries of the microdisks were defined in the polar coordinates according to as $\rho = R_0 + d(\sin \phi)$.

4.2 Fabrication

To fabricate the FSC microdisks, a 250-nm-thick layer of hydrogenated a-Si was deposited on a fused silica substrate by plasma-enhanced chemical vapor deposition using silane at 190 °C. A ~250-nm-thick layer of a negative electron beam resist (AR-N 7520.11 new, Allresist GmbH) was coated on the a-Si layer and baked at 90 °C and then a layer of conductive polymer (AR-PC 5091, Allresist GmbH) was spin-coated on the resist and baked at 50 °C to serve as a charge dissipation layer. The resonators’ pattern was written on the resist using a 125-kV electron beam lithography system (ELS-F125, Elionix). Subsequently, the charge dissipation layer was removed using deionized water, and the resist was developed for 1 min in a developer (AR 300-47, Allresist GmbH). The resist’s pattern was then transferred to the a-Si layer by inductively coupled reactive ion etching in a mixture of SF$_6$ and CF$_4$ gases, and the resist was removed using a solvent (Remover PG, Kayaku Advanced Materials Inc.).

4.3 Characterization

The transmission spectra of the FSC microdisk resonators were measured using the setup shown in Figure S4. Polarized light from a tunable laser (AQ4312A, Ando) covering the 1480–1580 nm range was amplified using an optical amplifier (FIBERAMP-BT 20, Photronics), passed through a manual polarization controller (FPC560, Thorlabs), and was free-space coupled using a fiber collimation package (F240FC-C, Thorlabs). A fiber-coupled visible laser was also coupled to the same collimation package using an optical switch (EK703-FC, Thorlabs). The output beam was sampled using a beam splitter (BP108, Thorlabs) and the reflected power was monitored using a photodetector (PDA10CF, Thorlabs) and was used for the normalization of incident power. The beam transmitted through the beam splitter was focused through the substrate on a resonator using an objective lens ($\times20$, 0.5NA, PE IR PlanAPO, Seiwa Optical). Light
transmitted through and scattered by the resonator was collected by another objective lens (×100, 0.85NA, IR Plan, Nikon Hamamatsu) and was measured using a free-space-coupled photodiode (FGA01, Thorlabs) and imaged using an infrared camera (MicronViewer 7290A, Electrophysics). The resonator sample was mounted on a three-axis translation stage equipped with piezo actuators with submicron resolution (Picomotor Actuator, Newport Corporation) for accurate alignment of the resonators to the focused incident beam. The visible laser light reflected from the sample was imaged using the illumination objective lens and a tube lens (AC254-200-A, Thorlabs) on a visible camera (EO-5012M, Edmund Optics), assisting the alignment.

The reflection spectra of the resonators were also measured using the setup shown in Figure S4 by exciting the resonator with a tunable laser through the ×100 objective lens. The same objective lens also collected the reflected light, and the reflected light was sent to a fiber-coupled photodetector (ETX 75, IDS Uniphase) using an optical fiber circulator (6015-3-FC, Thorlabs).

The quality factor values reported in Figure 3e and S5b were obtained by fitting the measured resonant line shapes of the transmission spectra to $T(\omega) = |a(\omega - \omega_0) + b\ell\phi|^2$, where $\omega_0 = \omega_0(1 + \frac{1}{Q})$, and using real-valued parameters $a$, $b$, $\phi$, $\omega_0$, and $Q$ as the fit parameters (Figure S5a).

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