Efficient micro-resonators simultaneously require a large quality factor $Q$ and a small volume $V$. However, the former is ultimately limited by bending losses, the unavoidable radiation of energy of a wave upon changing direction of propagation. Such bending losses increase exponentially as $V$ decreases and eventually result in a drop of $Q$. Therefore, circular cavities are generally designed with radii that are much larger than the optical wavelength. The same leakage of energy by radiation limits the sharpness of bends in photonic integrated circuits. In this Letter, we present a way to reduce bending losses in circular micro-resonators. The proposed scheme consists in one or more external dielectric rings that are concentric with the cavity. A proper design allows one to tune the near field of the cavity and alter the associated radiation field. As a result, the $Q$ factor can be increased by several orders of magnitude while keeping a small cavity volume.

In large cavities, the $Q$ factor is limited by parasitic absorption and scattering. By minimizing these losses with state-of-the-fabrication techniques, $Q$ in the order of $10^{11}$ have been demonstrated [39] while values in excess of $10^{10}$ have been reached in various photonic integrated platforms [40–45]. However, this is no longer true as the cavity radius $R$ becomes smaller than about ten wavelengths. Indeed, radiation losses associated to the bending of light trajectories increases exponentially with curvature. They are therefore the main physical obstacle to reduce $V$ while preserving $Q$.

In this Letter, we propose a general procedure to reduce bending losses, which can readily be implemented with existing technologies. It consists of surrounding the circular cavity with properly designed concentric dielectric shells. These give control to the far-field amplitude and, hence, the radiation losses of WGM. The more external shells there is in the external structure, the stronger the reduction of bending losses can be obtained, with no apparent limit. As an example, we show an increase of the $Q$ factor from 15 000 to 125 000, 600 000 and 2.5 $10^6$ with one, two or three external rings, respectively (here, and from now on, we restrict our attention to the radiative part of the $Q$ factor.) In another, extreme case, we consider a WGM with orbital number $\nu = 5$ and vacuum wavelength $\lambda = 1.26\mu m$ in a cavity with $R = 1\mu m$ only. Starting from an initial quality factor $Q = 12.3$, we obtain $Q > 4000$ by adding five external shells, while keeping the WGM entirely within the cavity. The strongest suppression of radiation is generally obtained when the innermost external shell is in the near field of the WGM. Conversely, if desired, the external structure can drastically enhance radiation losses and decrease $Q$. Hints that radiation losses could be controlled by such a structure were found by an analytical theory in the large-$\nu$ limit with a single outer shell [46]. Here, we provide a complete theory, valid for arbitrary $\nu$ and any number of external shells. It is important to note that, since it is the near-field that is primarily engineered, and since the material used is transparent, the external...
structure does not simply reflect the light that is radiated away by the WGM. In addition, the field stays confined in the internal cavity and the external shells that we design are usually too thin to guide light. This, together with the magnitude of improvement found here, makes the present study completely distinct from previous studies involving similar-looking geometries [47–51]. Finally, note the difference with Bragg fibres [52, 53] where propagation is along the axis of symmetry and the cladding is implicitly assumed radially periodic.

An analytical understanding of the radiation of a WGM resonator embedded in such a dielectric ‘sarcophagus’ can be obtained in 2D. In this framework, the knowledge of the electromagnetic field is entirely encoded in just one of its component, $\psi = E_z$ for transverse electric (TE) modes or $\psi = H_z$ for transverse magnetic (TM) modes. In an annulus defined by $r_{j-1} < r < r_j$, of refractive index $n_j$, the general form of $\psi$ is

$$
\psi = [a_jJ_\nu(n_jkr) + b_jY_\nu(n_jkr)]e^{i\theta -ikt \cdot \text{vector}}
$$

(1)

where $r$ and $\theta$ are the usual polar coordinates, $c$ is the speed of light in vacuum, $J_\nu, Y_\nu$ are Bessel functions of the first and second kind [54] and $k$ is the complex wave number. At surfaces of discontinuity of the refractive index, both $\psi$ and either $\partial \psi/\partial r$ (TE) or $n^2\partial \psi/\partial r$ (TM) are continuous. These continuity relations can expressed as

$$
\begin{pmatrix}
  a_{j-1} \\
  b_{j-1}
\end{pmatrix} = S_j
\begin{pmatrix}
  a_j \\
  b_j
\end{pmatrix},
$$

(2)

where the $S_j$ are $2 \times 2$ matrices containing combinations of Bessel functions evaluated at appropriate interfaces (see Supplementary Information.) By iterating the process, one may link the innermost and outermost coefficients of Eq. (1), giving

$$
\begin{pmatrix}
  a_0 \\
  b_0
\end{pmatrix} = S(k)
\begin{pmatrix}
  a_N \\
  b_N
\end{pmatrix},
$$

(3)

with $S = S_1S_2\ldots S_N$. Above, we have imposed constraints on the combinations of Bessel functions near the origin and in the outermost region, namely to avoid divergence as $r \to 0$ and impose proper radiation condition in the far field. The second component of Eq. (3) directly yields the characteristic equation:

$$
S_{21}(k) + iS_{22}(k) = 0.
$$

(4)

It has complex roots of the form $k = k_r - ik_i$, from which the quality factor can be deduced as $Q = k_r/(2k_i)$. To study $Q$ by direct resolution of Eq. (4) for each choice of geometrical parameter set $\{r_j\}$ rapidly becomes intractable as the number of outer rings increases. However, our aim here is to study the effect of the external structure on the radiation properties of the internal one, i.e. to compare $k$ with the complex wave number $k^c = k_r^c - ik_i^c$ of the bare cavity. The latter is easier to compute, as it solves a simpler equation. Moreover, in the situations of interest, $k_i^c$ is by hypothesis not so small that it requires special numerical care. As the innermost layers of the whole guiding structures make up the bare cavity, we may write $S$ in Eq. (3) as $S = S^cS^s$, where $S^c$ and $S^s$ correspond to the cavity and the radiation shielding structure, respectively. By analogy with the above, $k^c$ satisfies the simpler equation

$$
S_{21}^c(k^c) + iS_{22}^c(k^c) = 0.
$$

(5)
Focusing on the solutions that correspond to perturbed Eq. (6), we obtain

\[ S_{22}^c(k_c^e) = 0, \quad k_c^e \approx -S_{21}^c(k_c^e)/S_{22}^c(k_c^e), \]  

where prime denotes derivative. In the situations of interest here, \( \nu \) not being very large, finding the root of \( S_{22}^c(k_c) \) does not pose a numerical challenge (for a large-\( \nu \) treatment, see [46].) Next, with \( S = S^aS^c \), Eq. (4) yields

\[ S_{21}^c(S_{11}^a + i S_{12}^a) + S_{22}^c(S_{21}^a + i S_{22}^a) = 0. \]  

Focusing on the solutions that correspond to perturbed modes of the bare cavity, we note that \( k = k_c^e + \Delta k \), with \( |\Delta k| \ll k_c^e \). Expanding Eq. (7) near \( k_c^e \) and exploiting Eq. (6), we obtain

\[ \Delta k \approx - \left[ \frac{S_{21}^c(S_{11}^a + i S_{12}^a) - S_{22}^c(S_{21}^a + i S_{22}^a)}{S_{21}^c(S_{21}^a + i S_{22}^a)} \right] \approx -ik_c^e \left[ \frac{S_{11}^a + i S_{12}^a}{S_{21}^c - i S_{22}^c} \right], \]  

where the elements on the right hand side are evaluated at the known value \( k_c^e \). Since \( \Delta k = k_c^e - k_c^e - ik_i \), the change in quality factor that results from the external structure is found to be:

\[ \frac{Q}{Q^c} = \frac{k_c^e}{k_i} \approx \text{Re} \left[ \frac{S_{22}^c(k_c^e) - iS_{21}^c(k_c^e)}{S_{11}^c(k_c^e) + iS_{12}^c(k_c^e)} \right]. \]  

The advantage of the above expression is that it explicitly yields the ratio \( Q/Q^c \) without having to solve the characteristic equation of the complete geometry. It proves to be extremely accurate for values of the orbital number \( \nu > 10 \) (see Fig. 1.) Even for \( \nu = 5 \) does it predict the enhancement of \( Q \) to within fifteen percent. There has been a few previous works (see [46] and references therein) to estimate the losses in the asymptotic cases of large circular orbital number \( \nu \). However, to our knowledge, an analytic formula such as Eq. (9) which is nearly exact has never been presented. The provided formula is very useful, particularly to optimise a shield with many shells where a numerical resolution of the characteristic equation is laborious. It enables us to circumvent the problems of solving the transcendental equation and merely requires evaluating the formula for various shield parameters.

The above analysis suggests a simple, layer-by-layer, design strategy. Starting form the bare cavity, one first considers a single outside shell with inner and outer radii \( r_a \) and \( r'_a = r_a + d_a \). To optimize the right-hand-side of Eq. (9) with respect to only two parameters \( r_a \) and \( d_a \) is a straightforward matter. The greatest single-step enhancement is usually seen with this first outer shell. While several local maxima in the gain \( Q/Q^c \) are found, see Fig. 1, the global maximum is typically found in the near-field of the bare cavity: given the outer cavity radius \( r^c \), \( r_a \) is below the turning point \( n r^c \) where the spatial field distribution switches from exponential to oscillating [46]. Subsequent improvements are then achieved by optimizing the parameters of a second shell structure, followed by a third one, etc. To demonstrate this procedure, we first consider an \( \text{Al}_2\text{O}_3 \) ring cavity (refractive index \( n = 1.65 \)) in air environment. \( \text{Al}_2\text{O}_3 \) has been demonstrated to be an advantageous, CMOS compatible, host for rare-earth dopant and holds great potential to integrate micro-lasers in photonic platforms [55–58]. The bare ring cavity has inner and outer radii given by 2.5 and 3.2\( \mu \text{m} \), respectively. We focus on the fundamental radial TE mode with orbital number \( \nu = 22 \), which corresponds to a wavelength \( \lambda \approx 1.26 \mu \text{m} \), in the emission band of Yb. Without a dielectric sarcophagus, \( Q^c \approx 15,000 \). With a single shell with parameters \((r_a, d_a) = (4.87, 0.23)\mu \text{m}\), an eight-fold increase of

FIG. 2. Field distribution \( \text{Re}(E_z) \) for a TE mode with \( \nu = 5 \) (see text). a: bare cavity; b: radiation with a single shell; c: radiation with five shells. The cavity outer radius is 1\( \mu \text{m} \).
$Q$ is obtained. Approximate four-fold increases are additionally gained with a second and third shell with inner radii and thicknesses $(r_b, d_b) = (5.63, 0.21) \mu m$, and $(r_c, d_c) = (6.3, 0.2) \mu m$, respectively, eventually raising $Q$ to $2.5 \times 10^6$ (see Supplemental Information.) This last value is close to the current intrinsic limit of $Al_2O_3$. Interestingly, Fig. 1 indicates that $Q$ can also be significantly decreased for other configurations; in that case, WGM radiation is enhanced by the external structure.

As a second example, we consider a ring cavity with only 1$\mu m$ outer radius and radial thickness 0.7$\mu m$, operating at $\lambda \approx 1.47 \mu m$, that is $\nu = 5$. Here, $Q^c = 12.3$, which is unacceptably low compared to the state of the art. Adding five layers, all of thickness $d = 0.25 \mu m$ and internal radii $(r_a, r_b, r_c, r_d, r_e) = (1.65, 2.3, 2.95, 3.6, 4.25) \mu m$ leads to $Q = 4112$, representing and enhancement by more than a factor 300. Fig. 2 shows the change in radiation intensity and demonstrates that the mode energy stays confined in the central part of the structure. Further improvement can be obtained with additional layers. We note in this example that the optimal value of $d$ is close to $\lambda/4n$. It is expected that $d$ tends to that limit in the far-field, as the WGM locally tend to plane waves and the shield becomes equivalent to a Bragg reflector.

It is intuitively clear that, as far as radial confinement is concerned, the 2D picture provides a faithful representation of WGM, even in 3D. Indeed the WGM on a sphere with orbital number $\nu$ have a radial dependence, and a characteristic equation, again controlled by Bessel functions, albeit of order $\nu + 1/2$ instead of $\nu$ [1]. The WGM on a sphere can thus be mapped onto those of a an infinite cylinder and the two spectra coincide up to the transformation $\nu \rightarrow \nu + 1/2$. On the other hand, spherical WGM can be strongly confined in the polar direction, with their intensity distribution confined in the immediate vicinity of the equator. Those particular WGM are almost unaffected if the sphere is truncated along parallel planes to the equator, which, in turn, is geometrically similar to a disk. From these considerations, we expect that 2D cylindrical WGM can serve as a reasonable qualitative model of WGM in ring and disk cavities of finite vertical height and that our finding can be transposed there. To check this assertion, we have performed 3D simulations of SiO$_2$ disk cavities on a pillar over a Si foundation, as in Figure 3. Such a configuration, or similar ones, can be made using xenon difluoride (XeF$_2$) etching through a silicon substrate [45]. Here again, we manage to obtain a nearly eight-fold enhancement with a single external shell. With a second external shell the initial $Q$ can be improved further, up to a factor 26. This confirms both the fact that the quality factor can be increased by the design of an external shell and the fact that further enhancement can be obtained by additional shell. Hence, the gain reported in these 3D simulation should by no means be considered as ultimate ones. We have also considered ring cavities made of ridge waveguide and observed the same effect. Finally, note that the vertical confinement renders possible the excitation of the cavity in the presence of the external shells. For in-

![FIG. 3. Mode distribution (logarithmic color scale) of a SiO$_2$ disk cavity over a Si base. Cavity radius and thickness: 4.78$\mu m$ and 0.8$\mu m$, respectively. First shield inner radius and thickness: $r_a = 5.87 \mu m$, $d_a = 0.33 \mu m$. Second shield: $r_b = 6.84 \mu m$, $d_b = 0.23 \mu m$. Height of both shields: 5$\mu m$. Vacuum wavelength: 1.27$\mu m$.](image-url)
stance, ridge-waveguide cavities can efficiently be excited with buried waveguides [43, 58].

In conclusion, we have devised a way to control one of the most basic limiting factor to WGM resonator performance. With existing fabrication techniques, radiation losses can in principle be reduced to any desired degree on integrated photonic platforms. In the ratio $Q/V$, the quality factor could thus be limited by material factors only and not by bending losses. This could pave the way to orders of magnitude improvement of performances in laser operation, sensing or cavity quantum electrodynamics experiments based on WGM.

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