Single transverse mode optical resonators

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Abstract: We use quantum mechanical analogy to introduce a new class of optical resonators with *finite deflection profile mirrors* that support a finite number of discrete confined transverse modes and a continuum of unconfined transverse modes. We develop theory of such resonators, experimentally demonstrate micro-optical resonators intrinsically confining only a *single transverse mode*, and demonstrate high finesse *step-mirror-profile* resonators. Such resonators have profound implications for optical resonator devices, such as lasers and interferometers.

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1. Introduction: transverse spatial modes of optical resonators

Optical resonators, or cavities, consist of two or more mirrors that provide multiple reflections to confine an optical beam spatially in one or more dimensions. The mirrors can be planar or curved, where the curved profile is usually spherical. Optical resonators are a ubiquitous fundamental building block in optics, both for active and passive optical devices [1] and are used across a wide range of applications from lasers to spectroscopy and to sensors. In all lasers, resonators provide optical feedback required to achieve lasing; in interferometric spectral filters, such as Fabry-Perot interferometers, resonators provide the required narrow spectral resonance. Optical resonators have longitudinal modes characterized by optical field distribution along the optical, or beam propagation, axis. In turn, each longitudinal mode has a set of corresponding transverse modes that characterize optical field distribution transverse to the optical axis. Different longitudinal and transverse modes typically have different resonant frequencies. Importantly, *fundamental transverse mode operation* of an optical device is required when the higher-order transverse modes are detrimental to the device function because of their *differing spatial profiles* or *differing resonant frequencies*. For example, for *spatial profile reasons*, fundamental transverse mode operation is required of a laser for focusing its beam into small spots, such as in optical recording, or for coupling into single transverse mode optical fibers common in optical fiber communication. Also, long distance low diffraction free space optical beam propagation requires fundamental transverse mode laser source operation. On the other hand, for *spectral reasons*, single frequency, and thus also fundamental transverse mode operation, is required for lasers and interferometric filters used for communication and spectroscopy, where multiple higher order modes cause spectral dispersion or spurious spectral signals in measurements.

Intrinsic single transverse mode operation, while routinely achieved in optical fibers and critical for their application in long distance optical communication, has eluded optical resonators since invention of the laser more than forty years ago. In this paper we use an analogy with quantum mechanics to introduce a new class of optical resonators that can intrinsically confine only a *single transverse optical mode*.

Over the years, a number of techniques have been developed to control transverse modes of optical resonators [2]. *Spatial control* involves the use of intracavity beam apertures to introduce preferential loss for higher-order transverse modes [2]; some resonators use intracavity optical waveguides to provide spatial transverse mode control. Another approach is *spectral control* of transverse modes using confocal optical resonators [2], whereby selection of appropriate resonator geometrical parameters spectrally positions the transverse mode frequencies on a grid with half the spacing of longitudinal modes, thus minimizing interference for spectral measurements. These techniques of resonator transverse mode control are not always effective and a variety of optical devices are severely limited in their characteristics because of inadequate mode control. For example, semiconductor vertical-cavity surface-emitting lasers (VCSEL) emit only a few milliwatts of power in a single fundamental transverse mode, while with effective transverse mode control they are capable of multi-watt operation [3]. Micro-optical scanning Fabry-Perot interferometers is another example where single transverse mode operation is desired while the confocal approach is impractical in the micro-optical regime.

We use here an approach to optical resonators, whereby resonator *mirror profile* is viewed as an *effective potential* that shapes the transverse mode beam profile. Following this approach, we introduce resonators with *finite deflection profile mirrors* and demonstrate for the first time optical resonators that fundamentally confine only a *single transverse mode*. We also demonstrate, surprisingly, high finesse *step-mirror-profile* resonators. Finally, we discuss the unusual properties of these mode-controlled resonators. We believe this new class of resonators has profound implications for the science of optical resonator phenomena, for

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developing a broad range of novel optical resonator devices, such as lasers and filters, and for optical device applications, for example in communication and spectroscopy.

2. Effective mirror potential picture of optical resonators

We shall use simple two-mirror Fabry-Perot interferometers [1] to illustrate the basic optical resonator concepts, similar arguments can be applied to multi-mirror resonators. Such a resonator consists of two mirrors separated by a cavity length L_c and has a periodic comb of longitudinal modes with frequencies

$$f_m = m\frac{c}{2L_c} \tag{1}$$

where c is the speed of light, integer m is the longitudinal mode number, and the cavity length L_c is measured to the apex of the curved mirror. The filter period, or free spectral range, is determined by the cavity length and is given by the longitudinal mode separation. The finesse of such filters, defined as the ratio between the filter free spectral range and the mode spectral transmission bandwidth, is determined by the cavity mirror reflectivities, as well as possible intracavity optical loss. Moving one of the cavity mirrors changes cavity length and tunes the comb of longitudinal mode frequencies, which is commonly used for making tunable filters for spectroscopic measurements.

Turning to transverse mode properties, for planar mirrors the transverse modes of the cavity are spatially unconfined plane waves propagating at different angles to the optical axis. Curved spherical mirrors provide transverse spatial confinement; the transverse modes of such cavities can be described by Hermite-Gaussian functions in Cartesian coordinates or by Laguerre-Gaussian functions in cylindrical coordinates [2]. This classical picture of optical resonators had been developed in the 1960's by Fox, Li, Boyd, Gordon and Kogelnik [4,5,6], with a contemporaneous review in [7]. A historical perspective of the development of laser beam and resonator concepts in the 1960's and beyond has been given recently by Siegman [8,9]. According to this picture, an optical resonator with transverse mode confinement is produced when spherical profile mirrors are matched to the spherical phase fronts of the free space propagating Gaussian beams.

A well-known analogy provides a path beyond this classical picture: unfolding an optical resonator, one observes that it is equivalent to a periodic lens waveguide [10]. On the other hand, transverse mode properties of continuously guiding dielectric optical waveguides are well understood [11] and single transverse mode fiber waveguides are commonly used for optical communication. Indeed, drawing parallels between continuously guiding and discretely guiding lens waveguides, points to an approach to control resonator transverse modes and ultimately obtain single transverse mode resonators. To carry out this analogy between optical resonators and dielectric waveguides, we introduce a new concept of *effective length* of a resonator mode. For each longitudinal mode of the resonator with a resonant frequency f_m and longitudinal mode order m, there is a set of transverse resonator modes with resonant frequencies $f_{m,t} > f_m$ [2], where index t labels the transverse modes. Following Eq. (1) above for the longitudinal modes, we write a similar expression for the transverse resonator modes:

$$f_{m,t} \equiv m\frac{c}{2L_{m,t}} \tag{2}$$

which defines the *effective length* $L_{m,t} \equiv mc/(2f_{m,t}) < L_c$ of a transverse mode in terms of its resonant frequency. We also define the *effective deflection* $\Delta L_{m,t}$ of a resonator mode

$$\Delta L_{m,t} \equiv L_c - L_{m,t} \tag{3}$$

These concepts are illustrated in Fig. 1 for a plane-curved Fabry-Perot resonator with a spherical mirror. This figure suggests further analogies between the eigenvalue problems of optical resonators, dielectric waveguides, and particles in potential wells. Thus a potential well profile defines particle wavefunctions and energy levels, a waveguide refractive index distribution defines propagating optical mode transverse field profiles and propagation constants, and the resonator mirror profile defines the optical mode transverse beam profiles and mode effective lengths. For example, the harmonic oscillator with a parabolic potential well is analogous to a parabolically graded index waveguide and to the spherical, which is approximately parabolic near the apex, mirror resonator. These three cases have in common the parabolic shaping potential and therefore their modal eigenfunctions are Hermite-Gaussians and their eigenvalues are uniformly spaced. This analogy extends even further to the case of laser modelocking [12].

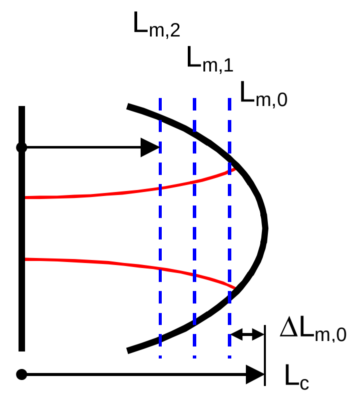

Fig. 1. Plane-curved optical resonator with effective lengths of its discrete transverse modes.

Why do harmonic oscillator and parabolically graded index fiber have “infinitely” many modes and how do we make a potential well or optical waveguide with just a single mode? The key to the answer is the depth of the shaping potential: the parabolic well has infinite depth, and thus supports an infinite number of discrete bound states [13]. A *finite depth* potential well supports only a *finite number of discrete bound states* plus a *continuum of unbound states* with corresponding energies below and above the edge of the potential well. Analogously, a finite index step optical waveguide supports a finite number of guided modes plus a continuum of unguided radiation modes [11] with corresponding mode effective indices above and below the cladding refractive index. Here the unbound or unguided modes are essentially plane waves just slightly perturbed by scattering from the potential well or the waveguide core. We conjecture that optical resonators behave analogously to potential wells and continuous dielectric waveguides: *mirror profile* acts as an *effective potential* that shapes the transverse optical beam profile, with mode effective deflections being analogous to the energy levels of potential wells and propagation constants of dielectric waveguides. If this conjecture is true, we should be able to make optical resonators with a single confined transverse mode by using resonator mirrors with a finite depth profile. This analogy between potential wells, optical waveguides, and optical resonators is illustrated in Fig. 2 for the finite potential depth case. The condition for a resonator transverse mode to be spatially confined is that its effective mode deflection $\Delta L_{m,t}$ has to be smaller than the resonator mirror maximum depth, or sag, d_0

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$$\Delta L_{m,t} < d_0 \tag{4}$$

We expect a finite-depth-mirror resonator to support a finite number of discrete confined transverse modes with $\Delta L_{m,t} < d_0$ and a continuum of unconfined modes with $\Delta L_{m,t} > d_0$.

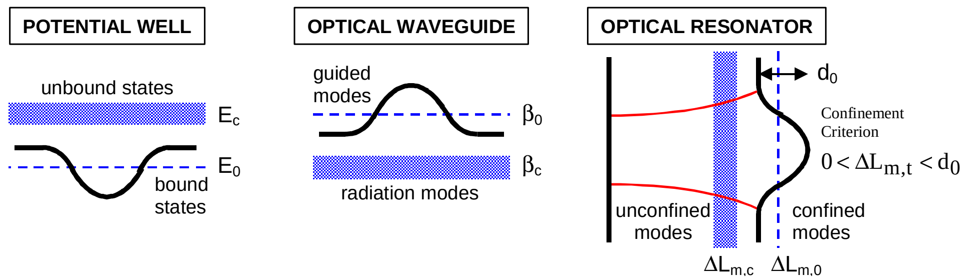

Fig. 2. Physical analogies: particle in a potential well, an optical waveguide, and an optical resonator, with their discrete bound and continuum of unbound states.

3. Calculated mode profiles, deflections, and the Λ-V modal diagram

We test our conjecture by calculating transverse modes of a finite depth mirror optical resonator. We consider plane-curved resonators with cylindrically symmetric mirrors, where transverse modes are characterized by a radial and an azimuthal mode numbers n_{rad} and n_{azim}. For convenience, we use an analytical secant hyperbolic mirror profile,

$$d(x) = d_0\left(1 - sec\,h\left(2r/r_0\right)\right) \tag{5}$$

Figs. 3(a) and 3(b) show transverse mode field profiles and effective mode deflections for a resonator with the deeper and shallower, respectively, secant hyperbolic mirror. Figure 3(a) shows modes with the azimuthal mode number $n_{azim} = 0$; the resonator supports only three ($n_r = 0,1,2$) such confined modes. The mode with the radial mode number $n_r = 2$ is approaching cutoff, as evidenced by its spreading field distribution, which is losing confinement, and by the mode effective deflection, which is approaching the mode cutoff condition $\Delta L_{m,t} = d_0$ of Eq. (4). Figure 3(b) shows the case of a shallow mirror; here there is only a single spatially confined mode for the azimuthal mode number $n_{azim} = 0$ and no confined modes for $n_{azim} \neq 0$. This is truly a single transverse mode resonator. Mode intensity profiles in finite deflection mirror resonators have exponentially decaying wings, unlike the Gaussian wings of the spherical mirror resonator modes. This is similar to the mode field profiles of finite index step dielectric waveguides. Unlike index-guided dielectric waveguides where the mode phase fronts are planar, the mode phase front in optical resonators is curved and matches the mirror deflection profile at the curved mirror.

We now connect resonator geometry with its transverse mode structure and determine resonator conditions that make it support only a single confined mode. A resonator becomes single mode when its first higher-order mode approaches cutoff and loses confinement. This condition can be determined approximately by fitting a spherical mirror that passes through the apex and the full width at half maximum (FWHM) points of the finite deflection mirror. This spherical mirror has a radius of curvature of $R_c = w^2/(4d_0)$, where w is FWHM and d_0 is the depth of the finite depth mirror. The transverse mode frequencies of spherical mirror

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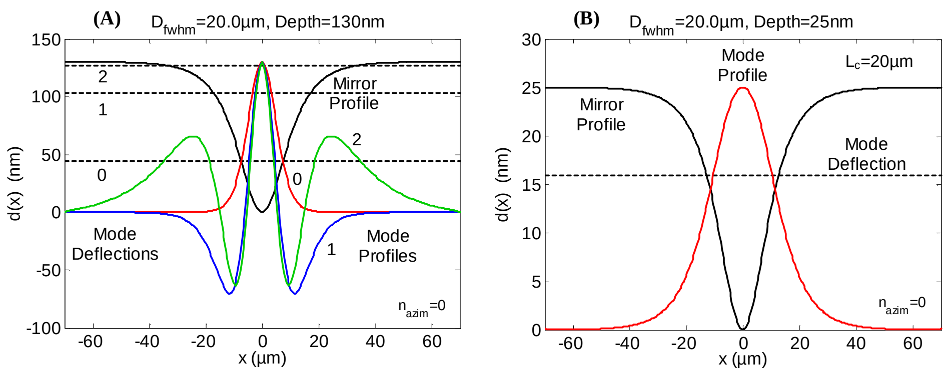

Fig. 3. Transverse mode profiles and mode deflections for a resonator with a finite depth secant hyperbolic mirror profile: (a) deeper mirror with three confined modes, (b) shallow mirror with a single confined mode.

resonators are well known [2]. Assuming mode frequencies of the finite deflection mirror resonator are approximately the same as for the spherical mirror resonator, we use the first higher order mode frequency of the spherical mirror resonator and its mode deflection in the cutoff condition of Eq. (4) to obtain an approximate single mode condition for the resonator:

$$V \equiv \frac{\pi w}{\lambda}\sqrt{d_0/L_c} < 2 \tag{6}$$

where λ is the wavelength of light. Compare this with the single mode condition of a step refractive index optical fiber

$$V_f = \frac{\pi w}{\lambda}\sqrt{n_{core}^2 - n_{clad}^2} < 2.405 \tag{7}$$

where w is the core width, n_{core} and n_{clad} are the refractive indices of the fiber core and cladding, and V_f is the well known fiber dimensionless universal parameter or V-number [11]. Similarity between Eqs. (6) and (7) leads us to believe that the geometrical dimensionless V parameter for optical resonators, as defined by Eq. (6), should define the mode structure of the resonators, as its fiber counterpart does for optical fibers [11]. Furthermore, to characterize the resonator transverse modes, we define a dimensionless mode deflection parameter Λ:

$$\Lambda \equiv 1 - \Delta L_{m,t} / d_0 \tag{8}$$

The Λ parameter ranges between 0 and 1 for confined modes and characterizes the strength of mode confinement by the mirror: Λ~1 corresponds to the strongly confined modes with mode deflection near the mirror apex; Λ~0 corresponds to the mode cutoff condition of Eq. (4) with mode deflection near the mirror edge d_0; for Λ<0 the modes are unconfined. For a resonator with a given V-number, we calculate the deflection parameters Λ of the different confined transverse modes; the resulting modal Λ-V diagram is shown in Fig. 4(a). The dashed lines in the figure were calculated using secant hyperbolic mirror profiles. For each V-number, we have used different combinations of resonator geometrical parameters, namely depth, width, cavity length and wavelength, all yielding the same V-number, and all have produced essentially the same deflections Λ on the Λ-V diagram, confirming universality of the V-number for characterizing resonator mode structure. Resonators with large V-numbers, support a large number of transverse modes. As the V-number decreases, higher order modes

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one by one loose their confinement as their Λ parameters decrease and reach mode cut-off condition Λ=0. Figure 4(a) indicates that resonators with secant-hyperbolic shaped mirrors become single mode when

$$V < 1.5 \tag{9}$$

which is similar to the approximate condition in Eq. (6). Using Eq. (9) and the V-number definition in Eq. (6) we find, for example, that for micro-optical resonators with cavity lengths of 10 to 50 μm, single transverse mode operation is achieved for mirror FWHM diameters of 10 to 30 μm and mirror depths of 20 to 80 nm.

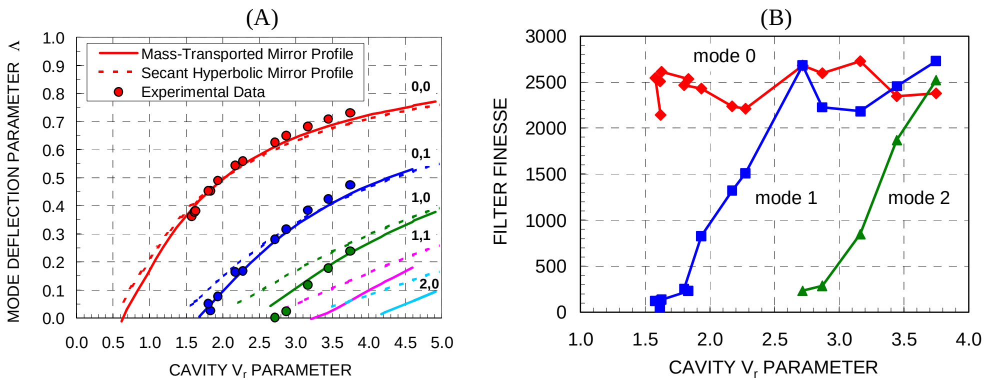

Fig. 4. (a) Calculated universal Λ-V diagram, with experimental data, for optical resonators with finite depth mirrors: mode deflection parameter Λ versus cavity V parameter for different transverse modes n_{rad}, n_{azim}; (b) measured finesse of three confined transverse modes as a function of the cavity V parameter.

4. Single transverse mode micro-optical resonators with curved and stepped mirror profiles

To demonstrate micro-optical single transverse mode resonators, we have used several different lithographically defined techniques to produce the required finite deflection mirror profiles on semiconductor substrates. One such technique uses mass transport [14] of an etched cylindrical pillbox profile to smooth out the etched edges and produce a mirror profile similar to the secant hyperbolic shape. Solid lines in Fig. 4A show the calculated Λ-V diagram for the mass transported mirror profile. For lowest order modes, the Λ-V diagram has only a small difference for the secant hyperbolic and mass transported mirror profiles, thus the detailed shape of the mirror profile is not critical for reaching the desired single transverse mode regime. We have fabricated such mass-transported mirrors with profile diameters between 17 and 30 μm and depths between 50 and 80 nm, and after high reflectivity optical coating assembled them with planar mirrors into ~23 μm long optical cavities. Solid points in Fig. 4(a) show the measured Λ-V diagram for these resonators, in remarkable agreement with the calculations. Figure 4(b) shows measured finesse of the three observed transverse modes as a function of the resonator V-number. The higher order transverse modes get cut off one by one as the V-number gets smaller: their normalized deflections Λ in Fig. 4(a) approach zero and their finesses in Fig. 4(b) drop rapidly to zero. Dropping finesse for higher order modes means their spectral resonances broaden and cavity transmission suffers increasing insertion loss. The fundamental mode finesse is preserved unchanged near the mirror reflectivity defined value. We reach single transverse mode resonator operation near V=1.6, as expected.

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Thus experimental observations confirm our original conjecture and model of optical resonators with finite deflection profile mirrors.

Figure 5 shows cavity filter transmission as the filter is tuned across a fixed wavelength laser, both for a conventional spherical mirror cavity and a finite deflection mirror cavity; for comparison, a reference Lorentzian lineshape is also shown. Note the inversions of the spectral scales between frequency and wavelength, as well as between filter center frequency scanned across a fixed laser line and an input signal frequency scanned across a fixed filter. When the input beam profile does not match the fundamental transverse mode profile of the cavity, the mismatched input power excites higher order transverse modes, whether discrete or continuous, evident in the spectra of Fig. 5. For the conventional spherical mirror cavity, the transverse mode spectrum consists of a fundamental mode and a multitude of equally spaced discrete higher order modes; here spectral degeneracy of the higher order modes is split by the small asymmetry of the fabricated mirror shape. Transmission spectrum of the finite deflection mirror cavity shows the fundamental mode, the residual first higher order transverse mode with broadened linewidth and thus severely reduced finesse, and the broad spectral continuum of the unconfined modes. The observed transmission spectrum in Fig. 5 is in agreement with expected transverse mode spectrum of finite deflection mirror resonators, as illustrated in Fig. 6. The spatially confined modes of such resonators are located spectrally between Λ=1, corresponding to wavelength $\lambda_m = 2L_c/m$, and cutoff condition at Λ=0, corresponding to cutoff wavelength $\lambda_{m,c} < \lambda_m$. Remarkably, the spatially confined mode spectral range

$$\lambda_m - \lambda_{m,c} = 2d_0/m \tag{10}$$

is determined only by the mirror depth d_0 and the longitudinal mode order m. For wavelengths below $\lambda_{m,c}$, there is a continuum of transversely unconfined modes. The unconfined modes have k-vectors tilted relative to the optical axis and in our cylindrically symmetric geometry have intensity profiles with periodic circular ripples spreading away from the mirror center, the ripple period decreasing with resonant wavelength decreasing below cutoff wavelength.

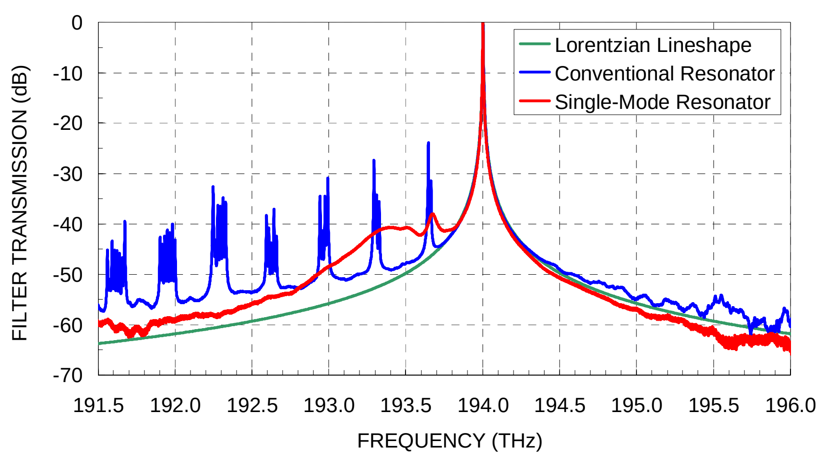

Fig. 5. Measured transmission spectra of spherical mirror and single-transverse-mode optical resonators: resonator fundamental mode frequency, plotted on the horizontal axis, is swept past a single frequency laser source by tuning the resonator via cavity length change.

In the realm of potential wells a frequent example is the rectangular quantum well, such as semiconductor quantum wells; for optical fibers, step index fiber is also very common. This

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raises an intriguing possibility of making by analogy a step mirror profile optical resonator. Conventional thinking suggests this should never work: there is no mirror "curvature" to focus the beam and there is strong diffraction at the sharp edges of the mirror step. To test our analogy, we have made stepped mirror profile Fabry-Perot resonators by etching a cylindrical pillbox shape in a planar Si wafer surface to make stepped mirrors. These resonators operated with a single transverse mode and high finesse: Fig. 7 shows measured finesse as a function of the mirror step diameter; inset in the figure illustrates resonator geometry. For comparison, Fig. 7 also shows the expected finesse of a plane-plane resonator with the same input beam diameter as the stepped mirror diameter. This plane-plane resonator finesse is more than fifty times lower than our measured step mirror resonator finesse because of uncompensated intracavity beam diffraction. Note that for the large diameter shallow step mirrors we are using, our high reflectivity optical coating does not change appreciably the step mirror profile. Measured finesse increases with increasing mirror step diameter, reaching values as high as 2000. Design mirror reflectivity here is 0.9990, and thus optical coating limited finesse is ~3000. Therefore these stepped mirror resonators do have intracavity loss; the roundtrip fractional loss is ~1×10^{-3} and ~4×10^{-3} at the measured finesse values of 2000 and 1000, respectively. This loss is sufficiently low and finesse is sufficiently high for a large range of potential applications for such stepped mirror resonators. We further speculate that even lower loss and higher finesse can be obtained by using multiple step, two or more steps, profiles to emulate continuous mirror profiles.

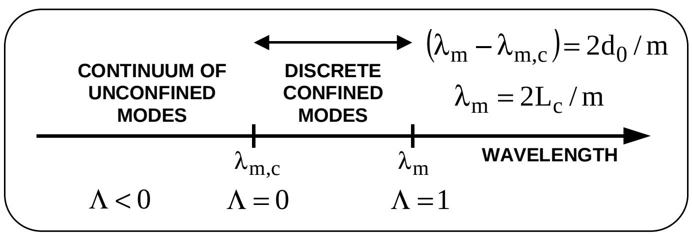

Fig. 6. Wavelength mapping of confined and unconfined transverse modes of optical resonators.

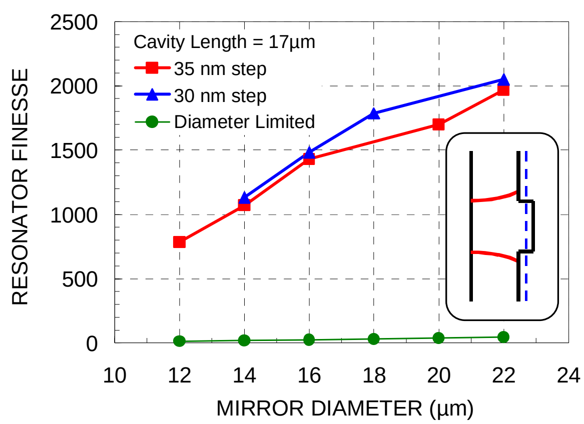

Fig. 7. Measured finesse of optical resonators with a cylindrical pillbox mirror profile as a function of the pillbox diameter.

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5. Properties of mode-controlled optical resonators

We have described optical resonator transverse mode control using finite deflection mirrors. Clearly, the same mode control can be accomplished using planar mirrors in combination with intracavity phase plates, finite deflection lenses or gradient index lenses. The requisite finite deflection phase profile can also be produced by the optical beam itself through a nonlinear optical phase change, such as a Kerr lens. Note that plane-plane resonators are just a particular case of the finite depth mirror resonators where mirror depth is zero and all transverse modes are part of the unconfined continuum.

It is instructive to contrast transverse mode control using intracavity apertures with that using finite deflection mirrors. Intracavity aperture in conventional resonators introduces effective spatial variation of mirror reflectivity *magnitude* and produces only *multimode passive* resonators with differential mode loss; it can potentially result in single mode laser operation only due to action of the active medium in the laser cavity. In contrast, finite deflection mirrors control transverse modes by effective spatial variation of reflectivity *phase*, while reflectivity magnitude profile can be uniform. Such resonators can be designed to support intrinsically only a *single* transverse *confined* mode in both *passive* and *active* resonator configurations.

In general, mode controlled optical resonators with finite mirror deflection have a number of properties quite different from their conventional, spherical mirror counterparts. For example, relative angular misalignment of the two mirrors in a spherical mirror resonator results merely in a transverse shift of the resonator optical axis. Angular mirror misalignment in finite deflection mirror resonators induces loss for the confined modes of the structure, as well as optical axis shift. In presence of relative mirror tilt, the confined transverse modes can diffract or “tunnel” out from the resonator “core” and couple to the unconfined modes of the continuum. This phenomenon is analogous to the bend radiation loss of optical fibers [11] or linewidth broadening in quantum-confined Stark effect [15]. Higher order transverse modes are more sensitive to mirror tilt than the fundamental mode. This can be used to achieve effectively single mode operation in large V number, large cross sectional beam area multimode resonators by tilting resonator mirrors and inducing loss for the higher order transverse modes. Similarly, single mode operation is achieved in high power multi mode fiber amplifiers by coiling the fiber to induce preferential bend loss for the higher order fiber modes [16].

Another unusual property is the effect on the mode-controlled resonator of the extraneous mirror bowing or intracavity lensing. If an otherwise planar mirror of the mode controlled resonator acquires a small positive curvature, for example due to stress bowing of a micro-opto-electro-mechanical membrane mirror or due to an intracavity thermal lens, an originally single-transverse-mode resonator can acquire additional parasitic confined transverse modes. On the other hand, small negative intracavity curvature would induce loss for the confined modes due to diffraction or “tunneling” of the modes out of the resonator core; higher order transverse modes are more sensitive to this curvature diffraction loss. This phenomenon, just as the mirror tilt loss, can also be used to one’s advantage by converting an otherwise multimode resonator to an effectively single mode one.

Optical resonators, which can be represented by effective discrete periodic lens waveguides, even though analogous, are clearly different from the continuously guiding dielectric waveguides. This is evidenced by the curved mode phase front of the resonators, compared with the flat mode phase front of the dielectric waveguides. Another manifestation of this difference is the measured finite loss of the stepped mirror resonators, while the step index fibers and rectangular quantum wells are intrinsically lossless. Can the finite deflection mirror resonators be intrinsically lossless, or do they have some loss which is dependent on the mirror profile shape and cavity parameters? We have demonstrated single transverse mode resonators with finesses up to 7000, so clearly resonator loss can be very small.

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There are many potential applications of single transverse mode optical resonators. For example, we have already used tunable single transverse mode micro-opto-electro-mechanical Fabry-Perot filters for spectral measurement of 1525 – 1610 nm wavelength signals in optical communication networks [17]. Optical resonators are also an intrinsic part of every laser, and thus mode-controlled resonators can be applied to lasers, such as VCSELs, which are limited, either spatially or spectrally, by the resonator transverse modes.

In conclusion, we have described a fundamentally new way of controlling transverse mode confinement in optical resonators, establishing a new paradigm in synthesis and application of these important optical functional elements.

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