High-Finesse Integrated Optical Microcavities for Use in Spectroscopy

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The potential of integrated optical microcavities for use in enhanced optical spectroscopy has been studied. These devices can sustain high morphological enhancement of optical field due to excitation of high-Q whispering gallery modes (WGM's). Estimations performed show that a local field in a microcavity can be increased by 2-4 orders of magnitude. A gain of $10^3 \div 10^7$ in detected Raman or fluorescent signal of a molecule put on top of the microcavity can be expected. We have fabricated high-Finesse integrated optics cylindrical microcavities that indeed provide fairly high enhancement of the optical field. The results obtained demonstrate feasibility of the microcavity-based device for optical spectroscopy.

Introduction

State-of-the-art optical techniques demand further improvement of both sensitivity and resolution of the optical components. This challenge has been addressed by creation of new types of sensitive micro- and nano-optical components capable of producing both localized and bright optical field. Localization of the optical field must exclude illumination outside the area of interest, while the high local field intensity must substantially (by few orders of magnitude) increase the sensitivity of conventional spectroscopic methods such as Raman and fluorescence. Yet enhancing properties of the probe are called for controllability and reproducibility. A promising approach to fulfill all these prerequisites is the use of an optical microcavity (MC) capable of field enhancement by many orders of magnitude [1,2]. Moreover, combination of a MC with integrated optics will deliver careful control and reproducibility required. In this work we present a first attempt to design, fabricate and characterize integrated optics MC's for use in optical spectroscopy.

Field enhancement in microcavity

Field enhancement in a MC originates from excitation of the so-called whispering gallery modes (WGM's) with extremely high Q. WGM's occur as a result of total internal reflection along a circular boundary of refractive index-contrasting materials with a resulted $Q > 10^{20}$, unless material and surface scattering losses considered [2]. WGM's in an integrated optics MC are excited by tunable laser light coupled to an adjacent waveguide (Fig. 1). The number of rotating intensity maxima around the circumference of the MC is given by $2l$, where l is the angular mode number, roughly determined by $l = 2\pi R/\lambda_{eff}$. A number of maxima in radial direction is determined by a radial mode order q (Fig.1).
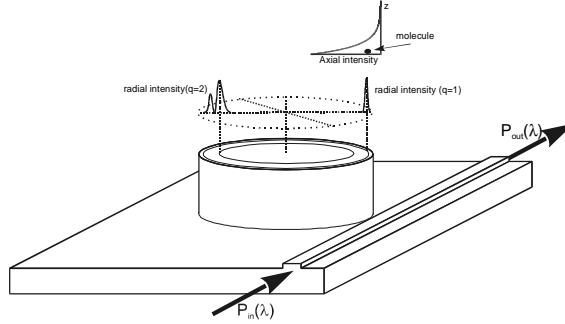
Figure 1. Radial and axial intensity distributions of the WGM's with two lowest radial mode orders.

For field localization and enhancement low order modes (q=1) are of advantage since they have largest Q and smallest radial extension. The bright "circle" of light intensity is essentially a bright source that can effectively boost Raman/fluorescence response of a molecule put on the top (Fig. 1).

Locally enhanced field results from a multiple constructive interference that takes place in a MC provided number of effective wavelengths in MC fits a roundtrip length [2]. Then an enhancement factor is effective number of field roundtrips conventionally given in terms of Finesse:

$$F \cong \frac{\lambda_r}{2\pi R n} Q \qquad (1)$$

where: R is the resonator radius, n is the refractive index and Q is the quality factor. The Finesse given by (1) relates the actual field in a MC versus field coupled in per single roundtrip. For spectroscopic purposes it is practical to use a global field enhancement factor G relating the actual field in the MC to the field in the waveguide:

$$G(\kappa) = \kappa \times F(\kappa) \qquad (2)$$

where κ is a field coupling factor or relative amount of field coupled into a MC per roundtrip. Implicit dependence F=F(κ) suggests that the waveguide near a MC equally affects both in- and out-coupling. "Loaded" F(κ) is always smaller than the intrinsic Finesse given by (1) and it is G(κ) that needs to be optimized for sufficient enhancement in a MC. The calculations of G for different intrinsic Q-factors are shown in Figure 2. The analysis of the curves shows that:

(i)   Field enhanced by more than $>10^4$ is feasible with devices of $Q>10^9$. Detected Raman or fluorescence signal of a molecule put on top of this MC can be boosted by at least 7 orders of magnitude

(ii) Higher intrinsic Q requires larger loading or field coupling κ

(iii) "Optimal" loading is achieved when the fraction of excitation field coupled into a MC per roundtrip exactly compensates roundtrip losses: $\alpha=\gamma/2Q$
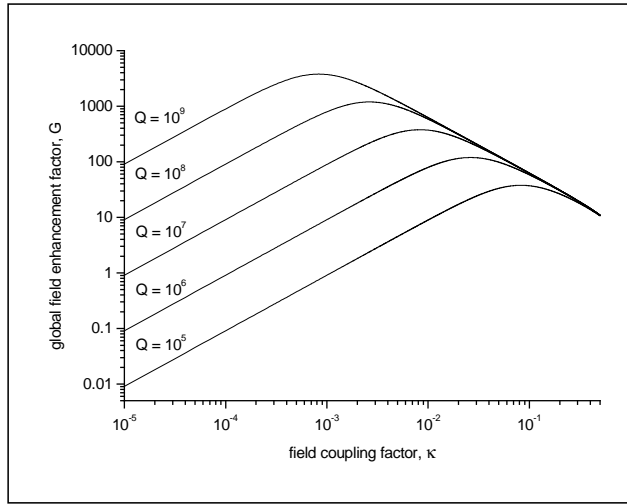
Fig.2 Global field enhancement factor in the MC vs. field coupling κ for 5 different values of intrinsic Q.

From practical point of view field coupling is determined by MC/waveguide separation and can be controlled at the design stage.

Experimental results

To explore the feasibility of integrated optics MC's for spectroscopy a series of devices with different waveguide/MC separations and different radii was implemented. Both scattering and transmission data were measured for the devices as a function of wavelength. Transmission data allow to quantify actual field in a MC and optimize coupling. In Figure 3 the CCD image of the MC together with the scattering cross-section is shown.
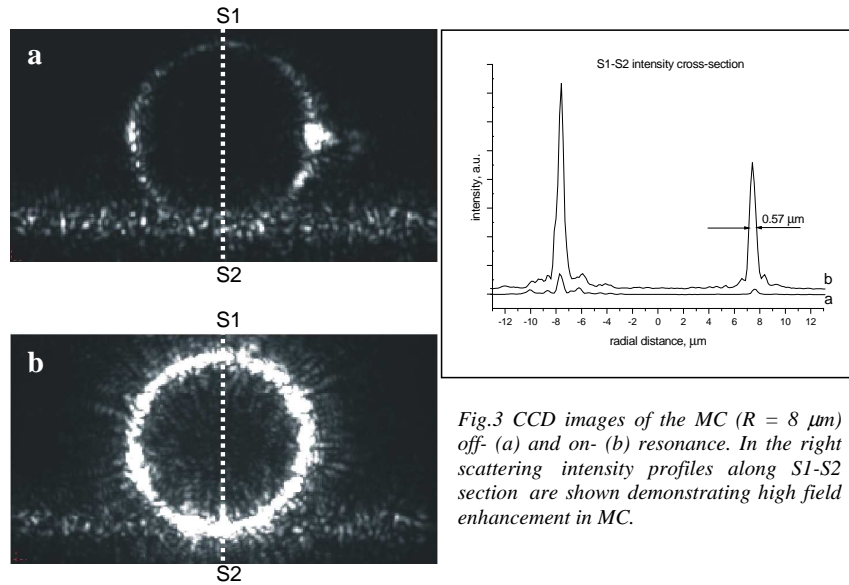

Fig.3 CCD images of the MC (R = 8 μm) off- (a) and on- (b) resonance. In the right scattering intensity profiles along S1-S2 section are shown demonstrating high field enhancement in MC.

As it clearly follows from comparison of the images and the scattering traces power in the MC on-resonance is more than a factor of magnitude larger than off-resonance. Moreover, >90% of the intra-cavity power is found at the rim of the MC corresponding to q=1 (Fig. 1). The radial extension of the mode profile is only 0.57 μm all along the circumference implying extra field confinement. Besides, tuning the excitation wavelength easily controls the enhanced power in the MC that makes the device a versatile tool for spectroscopy. Finesse of the MC's was measured in the range of 30-50 depending on the mode excited, and it is the high value of Finesse that allows field enhancement to occur and to be imaged. Finesse of our devices was an order of magnitude more than that of the first MC's made with the same technology earlier [3] and there is a clear motivation to improve it further for sufficient field enhancement as follows from Figure 2. Nevertheless, transmission measurements show fairly small power drop of 7-8% and therefore, the devices are not "loaded" optimally yet. Provided better phase matching, existing devices can be much improved both in terms of Finesse and field enhancement G.

Conclusions

We have proposed a new spectroscopic device based on a high-Finesse integrated optics MC capable of accumulating high local optical fields at its surface. Estimations performed undoubtedly show feasibility of the MC for field enhancement. We have implemented the first integrated optics cylindrical MC's and observed field enhancement in far-field imaging. In addition, we showed that enhanced field in the MC can be controlled and measured.

Acknowledgements

References

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