Mode filtering in optical whispering gallery resonators

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A method of suppression of unwanted 'transverse' modes in ultra-high Q optical whispering gallery resonators by use of radiative dampers is proposed and demonstrated.

Introduction: Optical domain filters are powerful new tools in a variety of applications. Their usefulness stems from their ability to filter any desired signal, at RF, microwave, millimetre, or terahertz frequency that is modulated as a sideband on an optical carrier. Optical whispering gallery mode (WGM) resonators fabricated with crystalline, and especially electro-optically active, materials [1] can be used as efficient high quality factor (Q) filters to detect microwave signals in the 1–300 GHz frequency range with a narrow (10 kHz to 10 MHz) bandwidth [2, 3]. The use of WGM resonator technology allows for designing filters with features of small size and weight, suitable for ground as well as spacecraft applications.

Recently we reported on the realisation of a miniature resonant electro-optically tunable filter [2]. The filter is based on a WGM disc resonator fabricated from a commercially available lithium niobate wafer. The filter can be characterised along the same lines as a Fabry-Perot filter. However, unlike a Fabry-Perot filter, the WGM filter typically has a dense mode spectrum. A large spectral mode density poses a limitation on the filter application in systems that require large sidemode rejection. A solution to reduce this limitation is the use of several coupled WGM resonators [3], though the sidemode rejection in that system would be even greater if each particular WGM resonator has a cleaner spectrum. Engineering the shape of the resonator's rim can clean up the resonator's spectrum [4], however fabrication of a resonator with the special shape is a complicated technological task.

We show in this Letter that the spectral density of most of the geometries of WGM resonators could be significantly reduced with application of specially designed mode dampers. A prism, or other polished piece of a material, with index of refraction higher than the index of refraction of the resonator material, can be used to strongly decrease Q-factors of most of the unwanted modes of the resonator. Ideally, only the modes of the main sequence survive. Q-factor of those modes changes only slightly in the mode rarefication process, which is tolerable for many applications. The selective suppression of the modes' Q's is possible because various WGMs are localised in various geometrical places (see Fig. 1). The ability of spectrum rarefication of an arbitrary WGM resonator after its actual fabrication significantly simplifies application of the resonator as a filter.

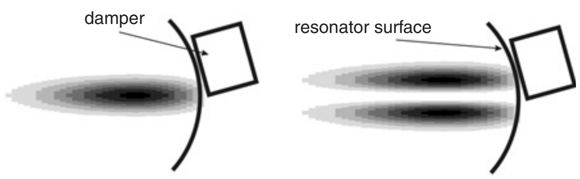

Fig. 1 *Localisation of electromagnetic field of two families of whispering gallery modes in toroidal WGM resonator*

Picture indicates schematic cross-sectional power distribution of modes in plane that crosses resonator and includes resonator's symmetry axis. Modes localised close to surface of resonator shown by solid curve and can be coupled from outside with a prism coupler. A coupler attached to the resonator as shown in Figure interacts with double-lobe mode, *b*, more efficiently than with singlelobe mode, *a*. As a result, Q-factor of double-lobe mode is suppressed

Experimental results: A scheme of a WGM resonator with a damper is shown in Fig. 2. We realised the system experimentally, fabricating the resonator with lithium tantalite and using a diamond prism as a spectrum cleaner (see Fig. 3). A Z-cut $LiTaO_3$ disk resonator has 12 mm diameter and 180 μm thickness. The disc rim is carefully polished to the spherical shape. We studied several nearly identical discs. The repeatable value of the quality factor of the main sequence of the resonator modes is $Q = 5 \times 10^7$, which corresponds to the 3 MHz bandwidth of the mode. Light is sent into and retrieved out of the WGM resonator via a coupling diamond prism (see Fig. 2). The repeatable value of fibre-to-fibre insertion loss with this technique is 6 dB. The maximum fibre-to-fibre transmission is achieved when light is off-resonant with the whispering gallery modes, while the maximum absorption is achieved for resonant light (stop-band filter). It is worth noting that a bandpass filter can be realised if two prism couplers are used [2, 3]. We utilised the stop-band configuration to demonstrate the validity of our spectrum cleaning method.

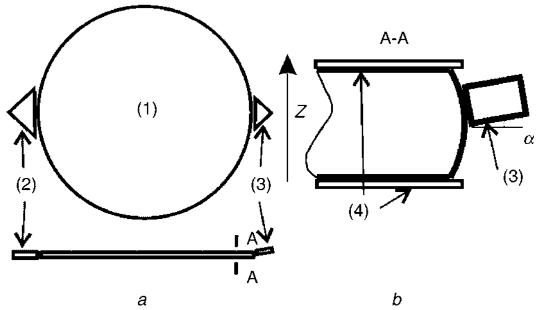

Fig. 2 *Schematic of WGM resonator-based tunable optical filter equipped with spectrum-rarefying prism dumper*

(1) resonator; (2) coupling prism; (3) dumper; (4) electrodes to tune resonator's frequency

Fig. 3 *Experimental realisation of $LiTaO_3$ WGM resonator with diamond dumper prism*

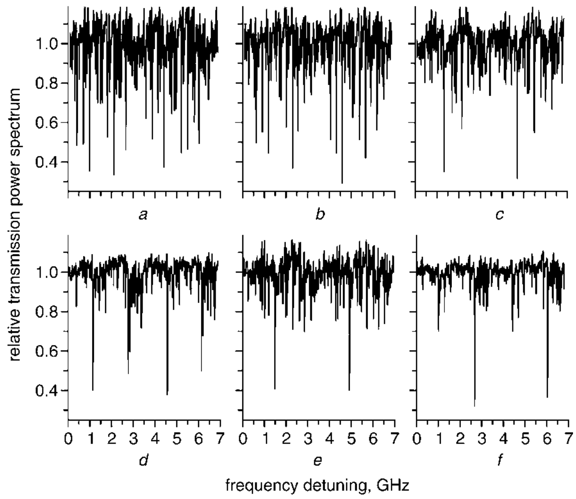

Fig. 4 *Normalised transmission power spectrum P_{out}/P_{in} through prism coupler (1) attached to $LiTaO_3$ WGM resonator (2) (see Fig. 2)*

Light passes through prism if its carrier frequency does not coincide with any resonance frequency of resonator. Spectrum in *a* is for resonator with no dumper attached. Spectra, *b–f*, for resonator with dumper attached (angle α (see Fig. 2) equal to 17°, 15°, 10°, 7°, 5°, respectively)

Our experiment demonstrates that proper application and tuning of the damping prism results in a significant cleaning of the mode spectrum (Fig. 4). If the spectrum of the resonator without the damper is very dense (Fig. 4*a*), the proper application of the damper leads to the rarification of the spectrum (Fig. 4*f*).

There is an optimum angle α which results in the cleanest spectrum of the resonator, as well as in the preservation of the high-Q main sequence of WGMs. For larger than optimum angle α, the modal spectrum is also rarefied, but not so significantly (Figs. 4*b* and *c*). This happens because in this case the damper coupling area is out of the region of localisation of the secondary modes interacting with the prism coupler (the modes that the damper is intended to suppress). Those unwanted modes are localised to the side of the resonator rim centre. Gradual decreasing of the angle towards its optimal value reduces their quality factors, which results in decrease of the coupling of these modes with the prism coupler. As a result, the modal spectrum becomes cleaner (see Figs. 4*d* and *e*). On the other hand, the smaller the angle, the stronger the damper coupling with the main mode sequence. To avoid a complete deterioration of the Q-factor of the main mode sequence the damper should not be in the same plane as the coupling prism, i.e. angle α should not be equal zero but be at an optimal value, which results in the spectrum shown in Fig. 4*f*.

We expect that our method will be especially useful in application to the multiple-resonator filters [3]. Rarefying each resonator spectrum will result in reduction of the floor of the entire filter. For instance, we have fabricated a three-resonator filter with −50 dB floor [3]. It is expected that cleaning of the spectra will result in an additional 10 to 20 dB floor reduction.

The WGM resonators with cleaned spectra are useful not only for filtering, but also for modulation of light. It was shown that a lithium niobate WGM resonator-based electro-optical modulator has a very high efficiency [5]. Because of its resonance characteristics, the modulator could be useful for applications in optoelectronic oscillators and modelocked lasers both as a filter and a modulator, to produce a low noise output of the device. However, the application of the modulator as a filter is hindered by the dense spectrum of the WGM resonators. The method, outlined in this Letter, solves the problem.

Conclusion: We have proposed and realised a method of cleaning the spectrum of an optical whispering gallery mode resonator. The resonators with clean spectra can serve as narrowband optical filters with a much lower floor as compared with the conventional crystalline optical whispering gallery mode resonators. The method can be understood as a transformation of a multimode resonator into a singlemode resonator, as if the resonator is fabricated with effective singlemode geometry, similar to the spectra of the lower Q ring resonators.

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