Investigation of coupling conditions in microgear resonators

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Abstract: In this paper, optical properties and coupling conditions for microdisk and microgear resonators are investigated under either pulsed or continuous wave excitation. Results for optimal excitation of microgear resonators in silicon-on-insulator technology are presented.

OCIS codes: (050.2770) Gratings; (060.1810) Couplers; (130.3120) Integrated optics devices; (160.3130) Integrated optics materials

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1. Introduction

A number of compact optical devices, including light sources, wavelength filters, submicrometer waveguides, optical resonators, can be realised using high refractive index contrast materials. Microdisk resonators supporting whispering gallery modes (WGM) are currently used in both passive and active devices. Lasers based on microdisk resonators have been fabricated with radius miniaturised to few micrometers while keeping a high quality factor [1-3]. The WGM is well known as the mode which propagates along the circumference of the disk. As the light seems to be in total reflection at the boundary of the disk, only a small part of the light leaks outside. As a result, these high quality factor microcavities allow low threshold with continuous emission by photoluminescence or injected current [4-6]. Microdisk resonators are multimode structures, supporting many modes of different azimuthal and radial orders. Fujita and Baba significantly improved this simple structure by introducing a Bragg grating at the circumference of the microdisk with a pulsation twice the azimuthal order of the WGM [7-8]. This structure is proved to be monomode and is called microgear resonator. The microgear selectivity comes from the scattering of the modes which do not match the Bragg conditions, leaving the microgear with two main modes. The "even" mode has its field extrema within the "teeth" of the grating and typically shows the quality factor increase with the increase of the grating depth for TE polarization. On the contrary, the "odd" mode, which has its extrema outside the teeth is confined within a disk of lower radius. The quality factor decreases with the increase of the grating depth.

Microdisks have been widely studied theoretically by many authors. Performance of a single microdisk and its coupling with a waveguide has been calculated using an analytical approach [9]. However, in most cases, a modification of the structure by deformation of the microdisk into a microgear is usually simulated using finite-difference time-domain (FDTD) computations [10], whose results are often in very good agreement with experiments [7]. Other numerical methods have been also used, including the perturbation scheme based on the coupled mode theory (CMT) [11], and the Floquet–Bloch approach [12]. In this paper, simulations of microdisk and microgear resonators are presented by using both 2D and 3D FDTD approaches [13-14]. For the first time, to the best of our knowledge, a detailed investigation of coupling conditions in microgear resonators, assuming excitation from an external input waveguide, is carried out. The study is carried out by varying a number of parameters (dimensions, wavelength, polarisation, gap, mode order). Single and double microgear configurations in both InP and SOI (silicon-on-insulator) technologies are analysed.

2. Excitation of resonators from an external waveguide

The aim of this section is to give the guidelines to investigate the coupling mechanism between an external straight waveguide and a microgear resonator evanescently coupled to it. To achieve this target, simulations has been performed to take into account the influence of the geometrical and physical parameters, such as radius, gap, grating height, azimuthal order mode and polarization. In addition, for a best understanding of the physical behaviour of the microgear resonator, comparison with microdisk cavities in terms of evanescent coupling efficiency and quality factor has been carried out. Finally, the influence of the technology has been evaluated comparing microgear resonators based on InP and SOI materials.

In Figs. 1(a) and 1(b) the single microdisk and microgear resonators, coupled to the external waveguide, are depicted respectively. As a first case, an InP waveguide has been chosen as in [12], with the height of 280 nm and effective refractive index of the core and cladding of n_1 = 2.63 (TE), 2.05 (TM) and n_2 = 1, respectively (InP substrate refractive index is 3.17). Its 2D effective index has been obtained by the effective index method (EIM).
The condition for exciting the whispering gallery mode with *m*-th azimuthal order is given by:

$$N = 2m \tag{1}$$

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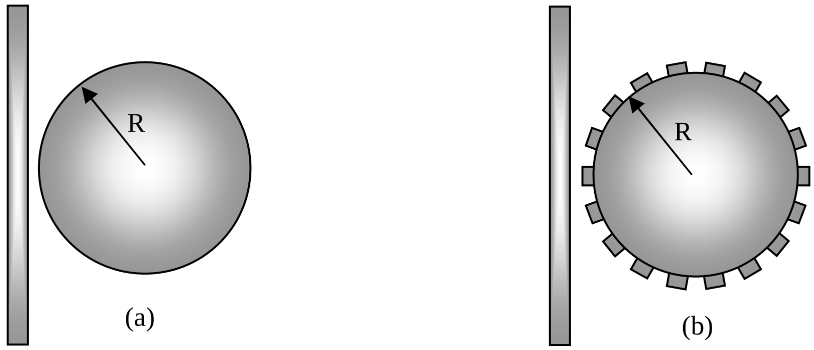
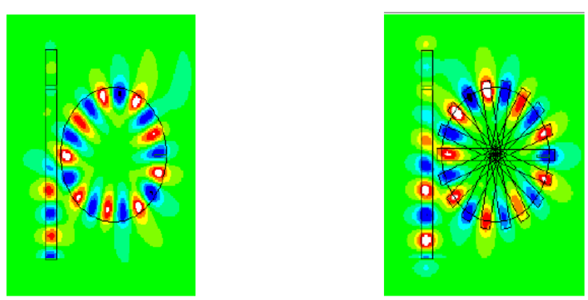


Fig. 1. (a) Microdisk and (b) microgear resonator coupled to the external waveguide, R being the internal radius.

Then, N = 18 teeth in the microgear have been selected with the aim to excite the order m = 9, using a radius of R = 0.9 µm. Of course, the microdisk can be seen as a microgear having a grating height equal to zero. In order to find the resonance frequencies of the microdisk and microgear structures, the first FDTD simulation has been carried out by exciting an external waveguide by a Gaussian pulse. An initial grating height of 0.1 µm has been chosen, while the gap between microgear and waveguide, 0.2 µm wide, was 60 nm. The simulation data included a grid size of 20 nm and a time step of 13.5 nm.
Considering the m = 9 azimuthal order mode, the resonance wavelength is equal to 1.2287 µm for microdisk and 1.3284 µm for microgear resonator, respectively. As further demonstration of the accuracy of this result, the resonators have been excited by means of a continuous wave (CW) at the resonance wavelength. Results have shown the presence of eighteen WGM peaks and high power coupled inside each resonator, as expected (see Fig. 2(a) and (b)). In particular, the power peaks in the microgear teeth (even mode) are more confined than in microdisk, allowing lower scattering as demonstrated from the reduced radiation field outside of the resonator.



(a) (b)

Fig. 2. (a) WGM peaks in microdisk and (b) microgear resonator coupled to the input waveguide.

This condition is important to improve the cavity quality factor, as it will be clear in the following analysis. It is worth noting that the previous FDTD simulations has been performed assuming the intrinsic losses inside the resonators equal to zero. Under this condition, some phenomenological considerations must be made about this different behaviour. In fact, while the microdisk is based on excitation of whispering gallery modes, the microgear resonator involves two different physical effects. The first is the building-up of the energy due to the resonant condition, and the second is the back-reflection induced by the grating. It is evident that the forward and backward propagating modes inside the microgear originate a pure

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standing wave, spatially distributed as a Bloch mode.

Moreover, an evaluation of the excitation time has been performed in both cases. It is defined as the time required to achieve the stationary regime in the process of CW excitation of the microcavity or, in other words, to excite the microcavity with an average power equal to that launched at the input section of external waveguide. This time has been demonstrated to be different in the two resonators, i.e. cT = 26.24 µm for microdisk and 33.74 µm for microgear, being cT an absolute time and c the velocity of light (note that T =1 fs corresponds to 0.3 µm). This means that, although the coupling is enough efficient in both cases, the coupling dynamics is faster in microdisk than in microgear. This different dynamics can be explained by introducing the time constant τ_e which is related to the power coupling process between microresonator and input waveguide. In the formalism of the coupled mode theory in the time domain (CMT), it is defined as $\tau_e = 4\pi R/(v_g \kappa^2)$ [15], where v_g is the group velocity evaluated at the resonance frequency and κ is the power coupling coefficient (see Fig. 1). Since CMT in the time domain leads to obtain good agreement with FDTD simulations both for travelling and standing wave cavity [15], then the previous formula is useful to draw phenomenological considerations about the FDTD results. Thus, the previous equation states that, for given values of radius and gap between bus waveguide and microresonator, the microgear induces a lower value κ with respect to the microdisk resonator, essentially due to the presence of the grating. Thus, as shown from the previous relationship, a smaller value of κ induces a larger value of τ_e and therefore a slower dynamics is expected in the microgear than in the microdisk.

After this analysis, we have considered microgear resonators in Silicon-on-Insulator (SOI) technology. In order to compare a SOI structure with the previous InP-based resonators, we have selected the structure dimensions such to excite again the mode order m = 9, by keeping the grating height constant, 0.1 µm, and selecting rib width of 0.2 µm, rib height of 0.3 µm and slab height of 0.1µm. Under these assumptions, Fig. 3 shows the resonance wavelength versus the internal radius in case of SOI technology. For example, the plot indicates that the resonance wavelength of SOI microgear resonator is best approximated to 1.55 µm when a radius of 0.93 µm is chosen.

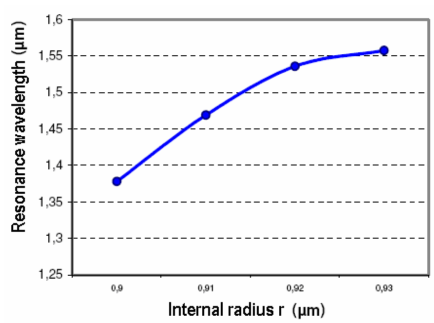

Fig. 3. Resonance wavelength versus microgear internal radius.

It is clear that stringent technological constraints should be satisfied to control this resonance wavelength. In fact, a variation of internal radius in the range 0.9÷0.93 µm (i.e. 30 nm) will induce a wavelength change from 1.3862 to 1.5576 µm.

The investigation of the coupling versus the gap between external waveguide and microresonator has been also carried out. Results are shown in Fig. 4, where the comparison between microdisk and microgear (plot a), and between the two microgear technologies (InP and SOI) (plot b), are plotted in terms of the resonator excitation time. It is clear that the dynamics is always faster (up to 30%) in microdisk than in microgear, although the difference tends to reduce with increasing the gap (up to 7% of reduction). Of course, the time increases

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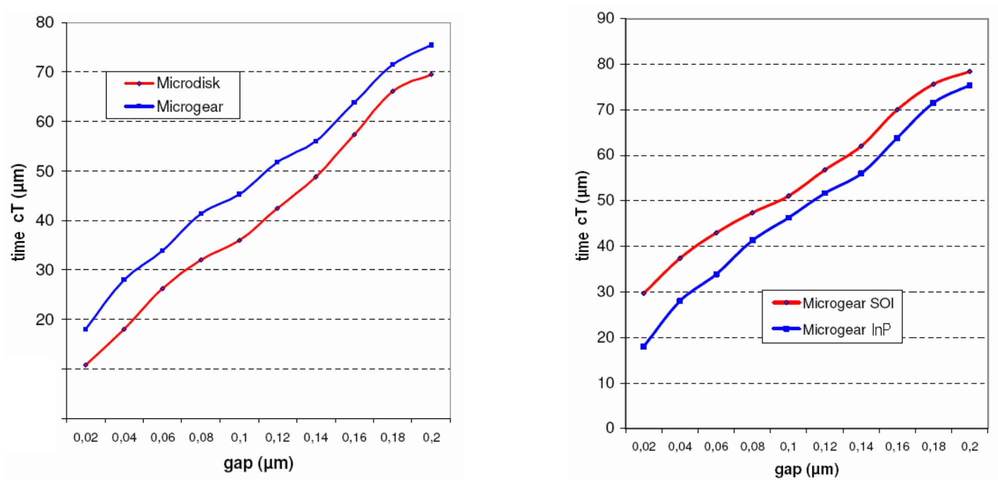
with the gap, because the coupling efficiency decreases. Moreover, the larger field confinement in SOI requires a longer coupling time than in the InP structure, as demonstrated in Fig. 4(b). Note that each microcavity is excited at its own resonance (1.5483 µm for SOI microgear, 1.3284 µm for InP microgear, and 1.2287 µm for InP microdisk).

Moreover, we have investigated the dependence of the resonance wavelength on the grating height in both microgear resonator technologies. Results for InP technology are shown in Fig. 5, where the point at zero height obviously corresponds to the microdisk case. A pulse has been again used in each case, in order to excite always the same WGM mode, $m = 9$. We can note a quasi linear behaviour, because the increase of grating height induces a linear increase of the resonator circumference and, consequently of the wavelength, which is related to the WGM mode having its peaks inside the grating teeth. Quasi linear dependence of the resonance wavelength on the grating height has been also observed for the SOI microgear resonator. A slight decrease of scattering effect outside the resonator has been observed with increasing the grating height, because the power confinement increases. Power transfer to higher order modes has been never revealed.



(a) (b)

Fig. 4. Coupling dynamics versus gap for microdisk and microgear structures (a) and for both technologies (b).

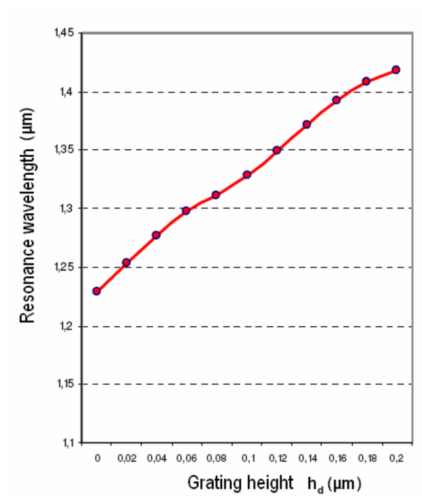


Fig. 5. Resonance wavelength as a function of grating height for InP technology.

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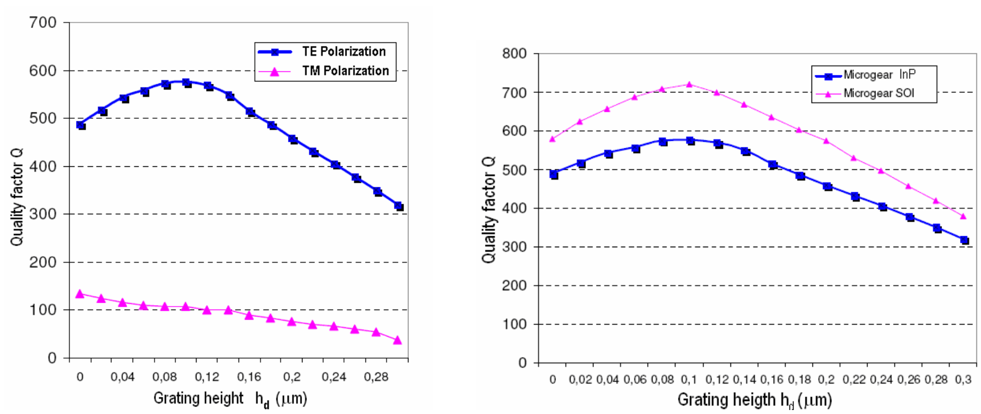
Another very important aspect of each resonator concerns its quality factor, defined as:

$$Q = \lambda_{RES} / 2\delta\lambda \tag{2}$$

where λ_{RES} is the resonance wavelength and $2\delta\lambda$ its full width at half maximum (FWHM). We have calculated this quality factor as a function of grating height for both polarizations, quasi-TE and quasi-TM. Results are shown in Fig. 6 again for the same mode, $m = 9$.

The two polarizations show a rather different behaviour. For InP technology Q has a maximum of 577 (Fig. 6a) for a height of 0.1 µm and quasi-TE polarization. In the microdisk (zero grating height), the factor is smaller, i.e. 489. In the case of quasi-TM polarization, the quality factor is significantly smaller, always decreasing with the grating height (Fig. 6(a)). All this means that the supported mode is even for TE polarization up to 0.11 µm, and, then, it becomes an odd mode, while the excited mode is always odd for TM polarization. Moreover, the high confinement allowed by high index contrast also means a larger quality factor in SOI versus InP structure, as shown in Fig. 6(b). A quality factor larger than 700 could be obtained for a grating height of 0.11 µm. Note that, in this phenomenological investigation of coupling conditions for microcavity resonators, the maximum value of quality factor is not an optimized parameter. Thus, larger values could be obtained in microresonators designed for specific applications.



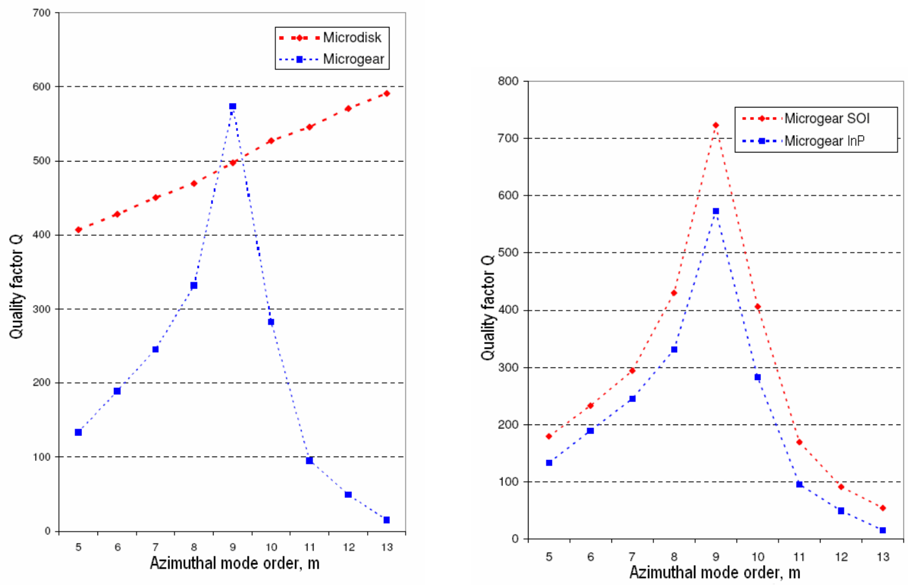
(a) (b)

Fig. 6. Quality factor versus microgear grating height for (a) both polarizations in InP and (b) InP and SOI technologies.

It is interesting to investigate the microcavity performance by changing the TE-polarized azimuthal mode order and keeping constant the grating height of 0.1 µm. Fig. 7 shows the quality factor versus mode order for InP microdisk or microgear (a), and for microgear resonators in different technologies (b).

It is clear that, while the microdisk has a multimode behaviour and presents a good quality factor over a large number of modes, the microgear is highly selective (monomodal) and can have better performance only for that particular mode satisfying the Bragg condition. For example, if $m = 10$, the quality factor is 527 for the microdisk but only 283 for the microgear. In fact, this mode cannot be well coupled in the microgear, and most of the power remains in the waveguide or is scattered outside the resonator. Further, SOI structure allows a better quality factor (due to larger index contrast) than for InP case for each excited mode, as sketched in Fig. 7(b).

The quality factor has been also investigated as a function of the gap between the InP resonators and the waveguide. We assume again a grating height of 0.1 µm and quasi-TE polarization. Fig. 8 shows that the InP microgear has higher quality factors than microdisk for each value of the gap.



(a) (b)

Fig. 7. Quality factor versus azimuthal mode order for (a) InP microcavities and (b) different microgear technologies.

The difference between the two structures decreases with the gap increase, whilst the coupling efficiency decreases. An unexpected minimum quality factor at 0.12 µm gap is clearly shown for both microdisk and microgear. For larger gaps, the resonance wavelength tends to slightly increase and the FWHM to decrease, giving an increased value of *Q*. However, for gaps larger than 0.25 µm, the coupling efficiency is very small giving a small value of *Q*.

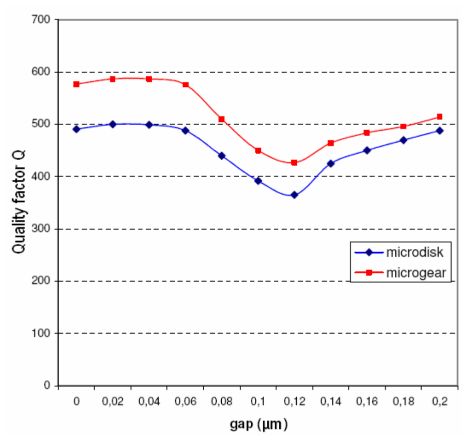


Fig. 8. Quality factor as a function of gap for both InP resonators.

As discussed previously, the microgear resonators can guarantee higher performance than microdisk only if a particular mode, satisfying the Bragg condition, is excited by the external waveguide. Field peak can be within the "teeth" of the grating increasing the quality factor, or on the contrary, outside the teeth within a disk of lower radius, thus reducing the quality factor. In both cases the Q factor can be maximised by decreasing the scattering losses related to the coupling process. Thus, it is evident that a rotation angle θ (misalignment) of microgear resonator with respect to the external waveguide, as sketched in Fig. 9, can induce some detrimental effects in the microgear behaviour.

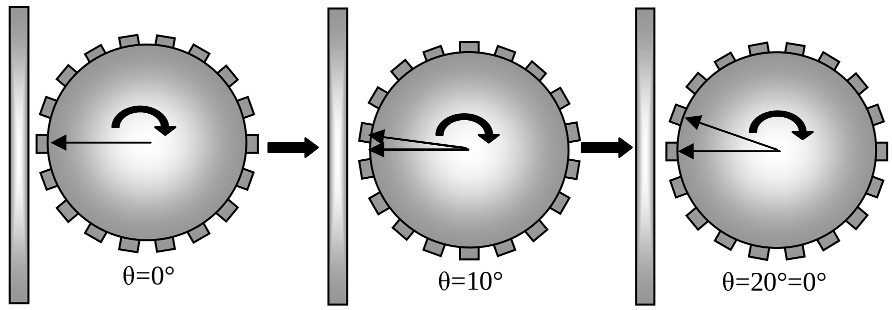


Fig. 9. Possible rotation misalignment of microgear resonator with respect to the external waveguide.

In Fig. 9, $\theta = 0°$ indicates the position of minimum distance between the grating tooth and the input waveguide, and then it represents the condition of optimum coupling. It is worth noting that in the case of $N = 18$ teeth the coupling is periodic with the period of $\theta = 20°$. This rotation can be basically seen as an effect of the fabrication tolerance. Fig. 10 and Fig. 11 show the coupling time and the Q factor versus the rotation angle for InP and SOI technology, respectively. The coupling time cT has been calculated by pulsed excitation of the resonator. Because of the symmetry, it is clear that the worst case (maximum coupling time) is obtained at the angle θ = 10°, as shown in Fig. 10. Although SOI structure has still a larger coupling time, a reduction of its dependence on the 'rotation' angle can be seen (12% compared to 15% for InP). This means that larger fabrication tolerances should be possible for higher index contrast structures, at the expenses of larger coupling time (coupling dynamics). The quality factor has been again calculated under pulsed excitation and is shown in Fig. 11 versus the rotation angle.

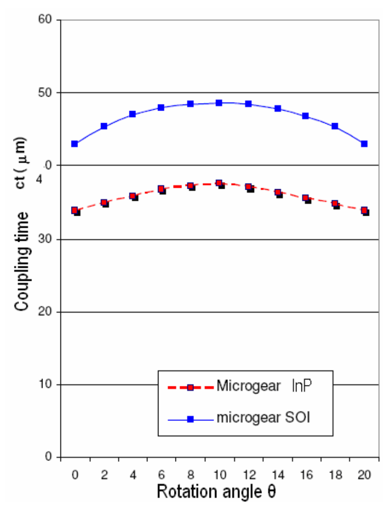


Fig. 10. Coupling time versus rotation angle for InP and SOI microgear.

The quality factor of the microgear has an opposite behaviour if compared with the coupling time. The maximum values are obtained for $\theta = 0°$ or $\theta = 20°$. Therefore, Q behaves similarly as in the case of the gap dependence (see Fig. 8).

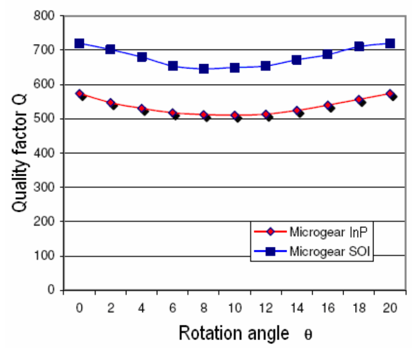


Fig. 11. Quality factor versus rotation angle.

3. Resonators coupled to both input and output waveguides

In this section both input and output waveguides coupled to InP microresonator are considered (see Fig. 12(a) for microdisk and (b) for microgear resonator).

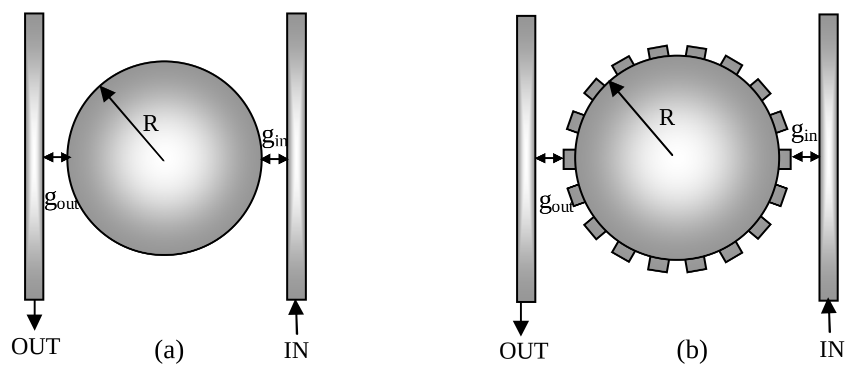


Fig. 12. Microdisk (a) and microgear (b) coupled to external input and output waveguides.

To set the gap values between the resonator and the input and output waveguides (g_{in} and g_{out}), we have considered as a first step the analytical formula related to the power ratio between output and input ports based on CMT in the time domain [15-16]. This relationship indicates the perfect travelling wave operation for a disk resonator without intrinsic losses to occur with $g_{in} = g_{out}$. However, in the presence of losses, the travelling wave behaviour can be again obtained by setting appropriate values for g_{out} and $g_{in.}$ By neglecting the intrinsic losses in our FDTD simulations we have assumed the condition $g_{in} = g_{out}$.

The microdisk has been excited at wavelength of 1.2287 µm, very close to the resonance condition, and the power remaining in the input waveguide or transferred to the second one has been time monitored. More than 70% of the launched power at the input can be coupled inside the resonator and, then, transferred to the second waveguide output. Of course, by setting the exact resonance wavelength the transferred power should be theoretically 100%.

Similar excitation of InP microgear resonator has been performed at 1.3284 µm (close to resonance). In this case, a maximum power of about 25% can be transferred from the input to the output, travelling in two opposite directions. This result is not surprising, since the Bragg grating of the microgear induces a backward wave to propagate inside the resonator. Thus, the presence of both a forward and backward wave induces a standing wave inside the microgear, that, in turns, precludes the possibility to have the travelling wave behaviour. Then, no net power can flow in one particular direction as observable in the disk resonator.

It is worth noting that the maximum power of about 25% transferred from the input to the output in two opposite directions is in very good agreement with CMT theoretical investigations about the standing wave resonator proposed in [15]. To further verify this, we have excited the resonator at other optimized wavelengths, 1.5790µm and 1.4178µm. Good power transfer (80%) is obtained but for different modes, m = 7 and m = 8, respectively. This means that the microgear behaves as a travelling-wave device, not standing wave, but at the expenses of much lower quality factor (see Fig. 7). To increase the power transfer from one waveguide to the other, the microgear should not be excited in some cases with a resonant mode, but in out-of-resonance regime. In fact, the mode should be not confined inside the teeth regions, favouring the external coupling as in a curvilinear directional coupler, with a maximum efficiency up to about 40%. However, the out-of-resonance behaviour is usually not useful in many applications.

4. Simulations of dual coupled microgear resonators

It is known that with two or more coupled resonators, one may modify the transfer characteristics from that achievable with a single resonator. For example, in the architecture of two coupled microrings proposed in [16], a 12 dB per octave roll-off rate outside of the resonance and a flattened resonant peak shape have been obtained. Further, a cascade of dissimilar resonators has the advantage of suppressing the resonances due to unwanted wavelengths through the Vernier effect. This can significantly increase the free spectral range over that of a single resonator. In addition, as demonstrated in [16], the microring cascade offers the possibility of realising desirable filter characteristics in close analogy with electrical filter design. In fact, an appropriate selection of coupling coefficients between the resonators allows to obtain two types of filter response, namely Butterworth and Chebyshev.

Therefore, a study of the architecture that includes two coupled microgear resonators is important and could be crucial to investigate the possibility to use a cascade of microgear resonators to synthesize optical filters with optimized characteristics. In Fig. 13 the architecture of two coupled microgear resonators used in the simulations is sketched. Since this architecture can be considered the building block for the a microgear cascade, the simulations are focused to select the best condition to maximise the coupling efficiency in the second microgear resonator.

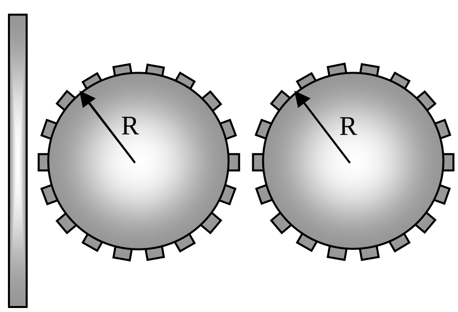


Fig. 13. Two coupled microgear resonators with an input waveguide.

Therefore, the situation with two coupled microgear resonators has been simulated by 3D FDTD approach in case of InP technology. The excitation of the second microgear is generally poor, with an efficiency of about 20%, because the standing-wave behaviour of the first

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microgear does not allow to increase the power transfer to the second one, as depicted in Fig. 14 for $m = 9$. A part of the power is also radiated outside the device.

Other excitation conditions have been investigated by changing either azimuthal mode order, grating height or resonance wavelength. However, the power transferred to the second microgear still remains low. Only under particular non resonant conditions (i.e. $m = 7$ and 1.5782 μm), where the first microgear is excited outside its resonance wavelength, a better coupling to the second resonant could be obtained with an efficiency larger than 40%. However, in this case the microgear should not have a resonant function, as before.

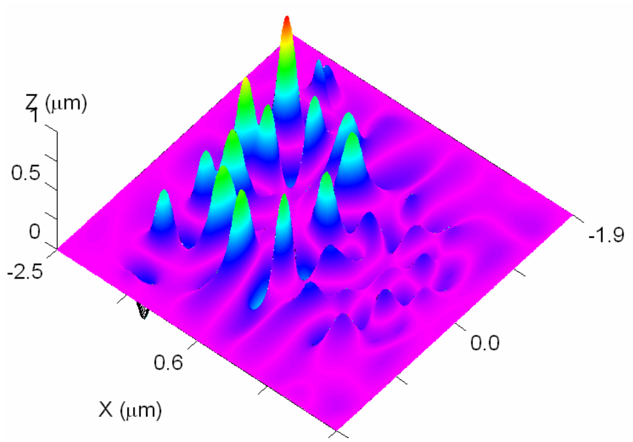

Fig. 14. 3D view of power coupled in two InP coupled microgear resonators.

Much better result can be obtained when we consider two coupled microgear resonators in SOI technology (see Fig. 15). High power level is coupled to the second microgear, because in this case the excitation wavelength, depending on the high index contrast SOI structure, is perfectly matched to the whole resonant microcavity, formed by the two coupled microgears. This is also due to the particular configuration of the two coupled cavities, being their teeth perfectly in phase, inducing two standing waves with the same symmetry. However, this is possible only if each power peak is exchanged from the tooth in the first microgear to the corresponding tooth in the second one, as it is clearly shown in Fig. 15. Under these particular conditions, the power confined in this dual coupled microgear structure could be larger than that confined in a single microgear resonator (giving larger quality factor and high filtering) because the FWHM is smaller for a double resonator structure. The excited WGM order is again $m = 9$, using the gap equal to 60 nm.

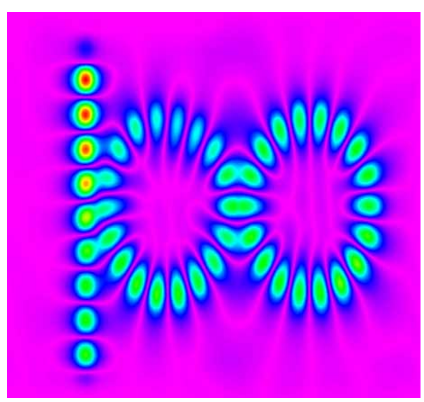

Fig. 15. 2D view of two coupled microgear resonators in SOI technology.

5. Conclusions

The microdisk and microgear resonators have been extensively investigated in this paper by finite difference time domain simulations. A number of parameters have been changed with the aim to find the best coupling conditions of power coming from an external input waveguide. Fabrication tolerances have been so defined. The standing-wave behaviour of these microgear resonators has been explained. Unexpected conditions of high coupling efficiency for one or two coupled microgear resonators have been found by considering high index contrast structures in silicon-on-insulator technology, where larger quality factors and less critical fabrication conditions can be found. This investigation allows to select the best coupling conditions for microgear resonators fabricated under different technologies (InP, SOI). In particular, SOI microgear resonators could be used in many applications including filtering and sensing, due to better optical confinement and integration with electronics on the same chip.

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