Dissipative coupling between ring resonators for large area, single mode lasing at visible wavelengths.

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It is well known that the coupling of two (ring) resonators results in bonding and antibonding supermodes with a different resonant frequency. Less known is that these modes also have a different Q factor. The bonding mode will show a longer decay time and hence a lower lasing threshold. This effect can be used to synchronize the two lasers when the resonator is used as a lasing cavity.

The effect however, can be quite small. In this contribution, we engineer the coupling and loss of micro-ring resonators to achieve strong dissipative coupling. Simulations of 10 um rings that resonate at 635 nm results in a difference in Q factor between simulated bonding and antibonding modes. We also show the potential of this coupling mechanism in the synchronization of larger laser arrays. Our results are a first step in the achievement of bright, on chip and large-area single-mode lasers in the visible wavelength regime.

Introduction

The optical ring resonator, together with its whispering gallery mode (WGM), is well-known. But also for ring resonators, the whole is more than the sum of the parts. Many interesting physical effects pop-up due to the coupling of two resonators. There is the splitting of resonance due to a bonding and antibonding mode, analogue to the splitting in energy levels in a H_2-molecule [1]. There is the well-known Vernier effect to increase the free-spectral-range of a filter when the rings have a different circumference [2]. When a gain material is added and the resonator is pushed into lasing action, exotic effects appear due to symmetry breaking [1].

All these effects rely on the overlap between the evanescent tale of the modes in the resonators and therefore direct transmission of light from one resonator to the other. This kind of coupling is sometimes classified as dispersive coupling [3]. On the other hand, dissipative coupling also exists. Here, there are interference effects in the light that leaks out of the resonators, resulting in lower or higher loss depending on constructive or destructive interference respectively. In this work, we show by simulations that dissipative coupling occurs when the rings are only shallow etched and are thus surrounded by a slab waveguide.

We envision the use of CdSe/CdS colloidal quantum dots as a gain material for later applications because of their mature and flexible hybrid integration. Hence the wavelength of interest in this study is 640 nm (470 THz). In this study, the ring resonators are characterized by a complex frequency in which the real part corresponds to the resonance and the imaginary frequency to the damping. The Q factor can then be calculated as $\frac{\mathrm{Re}(f)}{2\mathrm{Im}(f)}$ [4]

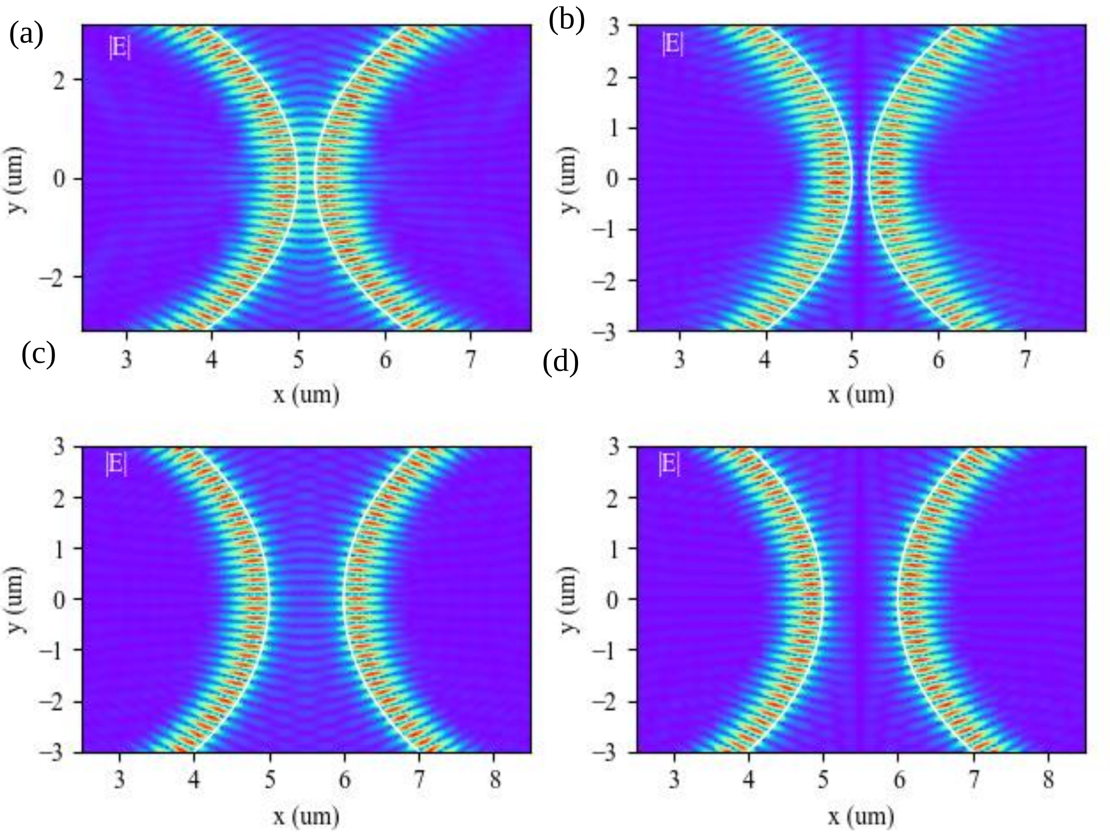

Figure 1: mode profile of (a) 200 nm gap in phase mode, (b) 200 nm gap out of phase mode (c) 1000 nm gap in phase mode (d) 1000 nm gap out of phase mode

Dissipative coupling

We simulate rings of SiN_x with a height of 170 nm, an inner radius of 3 µm and an outer radius of 5 µm. The rings are shallow etched and surrounded by a cladding of 130 nm SiN_x. For comparison, we also study the same structure with slab of only 100 nm around the ring. First, we performed an effective index approximation using Lumerical. The core and cladding index are respectively 1.74 and 1.46 for the TM mode in the structure with thick slab. The cladding effective index is 1.2 for the structure with the thin slab while the core index remains the same. In the remaining of this work, we use TM polarization.
For a single ring, a semi-analytical solutions exists [4]. The many WGM-solutions are distinguished by two mode numbers. The radial mode number represents the number of lobes the mode has along the radial direction. The azimuthal mode number represents the number of wave oscillations in each roundtrip. We chose a radial mode number of 1 (fundamental mode) and an azimuthal mode number of 79. The solution has a complex frequency of 466.5 - 0.009j THz. This means that this mode resonates at a frequency of 466.5 THz and has a damping time of 1/0.009 ps and the Q factor of this mode is 2500. This mode is two-fold degenerate, with a π phase shift between the degenerated modes.
Numerical tools are needed to simulate the coupling between WGMs in two coupled rings. We use two-dimensional electromagnetic frequency domain simulations (COMSOL). The results are shown in figure 1a and 1b for a gap between the rings of 200 nm. One distinguishes four modes with the same mode numbers. There are two in phase (bonding) and two out of phase (antibonding) modes, both of which are again two-fold degenerate by a π phase shift. We ignore this degeneracy for the remaining of the text.

The in phase mode, (figure 1a), has a lower frequency than the out of phase mode (figure 1b), causing a resonance splitting around 466.4 THz (which is close to the analytical obtained resonant frequency of a single ring). This splitting is shown in figure 2a as a function of the gap between the two rings. This splitting exponentially decreases as the gap becomes larger. For gaps above 1 µm, one can see some small oscillations as a secondary effect.
For the imaginary frequency, these oscillations are more pronounced (figure 1b). For gaps that are larger than the optical path length of one wave, we see a splitting in the imaginary frequency that is periodic with the gap size. When the gap is small, the imaginary frequency is larger than the single resonance case since the presence of the second resonator locally disturbs the mode profile and causes more radiative leakage in the rings. This coupled-induced loss reduces when the gap becomes larger. The mode profile is shown in figures 1c and 1d for in phase and out of phase modes. For the in phase mode case, the radiated light interferes constructively between the resonators, hence increasing losses. For the out of phase mode, there is destructive interference between the radiated light, hence lower loss. This interference phenomenon has a periodicity that corresponds to the cladding refractive index times the wavelength.

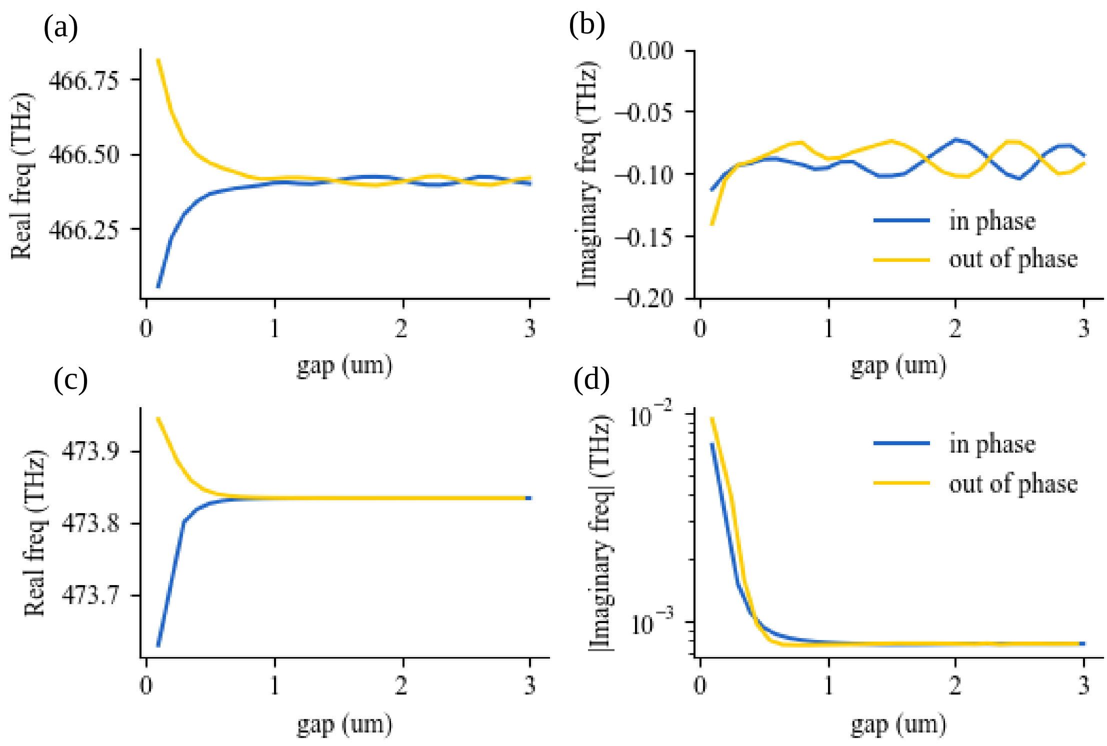

Figure 2: (a) and (b) show respectively the real and imaginary frequency of a system of two ring resonators with a cladding index of 1.47. (c) and (d) show the same quantities for a cladding index of 1.2.

When there is no slab present, the situation is as shown in figures 2c and 2d. The splitting in the real frequency shows the same exponential behavior. Splitting in the imaginary frequency only occurs in the coupling-induced loss when the rings are very close to each other, but is absent at larger distances. This shows the importance of the slab in the coupling mechanism.

Coupled mode theory

The behavior described above can be understood in terms of coupled mode theory. If each mode has a complex (angular) frequency of $\omega_R - j\omega_I$, and the coupling between the modes is characterized by the coupling strength κ, the eigenfrequencies of the coupled system are found by the eigenvalues of the following equation:

$$det\begin{pmatrix}\omega_R - j\omega_I & \kappa \\ \kappa & \omega_R - j\omega_I\end{pmatrix} = 0 \quad \Rightarrow \quad \omega = \omega_R - j\omega_I \pm \kappa$$

One can see that the splitting of the modes happens in the real (imaginary) frequency if κ is real (imaginary). This allows to capture the behavior of dispersive and dissipative coupling in a complex coupling constant. For example, when the gap between the rings is 1 µm, we have $\kappa = 0.007 + 0.004j$ THz.

As a last step, we use this coupled mode theory to get a prediction of the behavior of larger arrays of coupled rings. The equation above described an array of two rings. The same formalism can be used to expand the matrix to a 10×10 one in order to simulate an array of 10 resonators. The eigenfrequencies will again be complex and are found numerically. In figure 3, we show the 10 eigenfrequencies of the system when the coupling constant is real and complex. Recall that the lower the magnitude of the imaginary part, the higher the Q factor. A higher Q factor in its turn indicates a lower lasing threshold. This shows the usefulness of a complex coupling factor. In the latter case, one mode has a lower lasing threshold than all the other. Hence, only this mode will start lasing around the lasing threshold, creating a large synchronized laser [5].

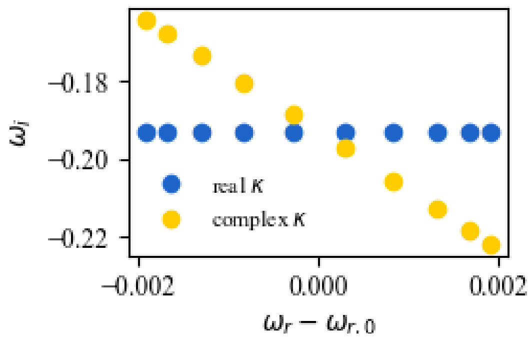

Figure 3: modes of a an array of 10 coupled rings. Dissipative coupling leads to one mode having the lowest threshold.

Conclusion

In this work, we showed that dispersive coupling occurs in optical microring resonators surrounded by a slab waveguide if the slab is sufficiently thick and the ring Q factor of the ring is thus low enough. This effect can be used in the synchronization of laser arrays.

References

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