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Tunable Fano-like resonances in bent single-mode waveguide-based Fabry–Perot resonator: erratum

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In this erratum, we correct an error in the numerical simulation results published in Optics letters 44, 2 (2019). The error arose from disregarding cladding modes in the straight input and output waveguide sections [Fig. 2(a) in the original paper]. Although these modes do not contribute directly to the calculated power in the reflected and transmitted fundamental modes in those sections, they do, nevertheless, play a significant role in shaping the reflection and transmission spectra of the bent resonator, as was found after the paper had been published. While the main findings of the original paper remain largely intact, quantitatively the spectra in Figs. 3–6 are inaccurate and must be replaced with the correct ones given in this erratum. Some minor modifications to the conclusions of the original paper that are required in view of the corrected results are also discussed.

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To verify the number of modes in each of the five sections of the bent waveguide structure shown in Fig. 2(a) (input straight waveguide section, first mirror, bent resonator, second mirror, output straight waveguide section) required for convergence of the numerical results, we have performed a mode convergence study. The study showed that at 60 modes or more in each of the sections (including cladding modes in the input and output sections) the modeling results become insensitive to the variations of the number modes in the simulation [1]. To ensure convergence with some safety margin, we have recalculated all the reflection and transmission spectra shown in Figs. 3–6 with 70 modes in each of the sections.

Figure 3 shows the reflection and transmission spectra of the bent resonator obtained for various bend radii around $R = 7.575$ mm, at which strong coupling occurs between the bent waveguide's fundamental (FM) ~~and whispering~~ gallery (WGM) modes at $\lambda \sim 1555$ nm. The reflection and transmission coefficients are defined, respectively, as the ratio of powers of the reflected FM in the input ~~fiber~~ section and transmitted FM in the output section to the power supplied by the incident fundamental mode in the input section.

Comparing the corrected spectra with those shown in Fig. 3 of the original paper, one can see that, apart from a slight change of the corresponding resonator parameters, the main distinction is that the splitting of resonances (shown with the red double arrow) occurs in a more smoothed out fashion, which is characteristic of the Autler-Townes splitting rather than electromagnetically induced transparency (EIT) or high Q-factor Fano resonance.

This is also true of the spectra shown in Fig. 4 which were calculated at the bend radii corresponding to the coupling of FM with WGMs of different orders. To emphasize the latter point we plot in Fig. 4(e) the effective indexes of the bent waveguide supermodes vs. bend radius at a fixed wavelength of 1555 nm. Indicated with vertical dashed lines in the figure are the bend radii at which the spectra in Figs. 4(a)–4(d) were obtained. Obviously, stronger splitting observed at smaller values of R results from the wider anti-crossings of the dispersion curves of the bent waveguide supermodes. This is an indication of a stronger coupling between FM- and WGM-resonators at smaller bend radii which ~~comes about~~ from larger overlap of FM and WGM profiles, as discussed in the original paper.

The effect of the gold mirror thickness on the bent resonator transmission and reflection spectra is illustrated in Fig. 5. As one can see from the comparison of the figure below with that in the original paper, the main distinction is the absence of the multiple narrow-band features previously observed at small mirror thicknesses. Those features should therefore be considered numerical artifacts bearing no physical meaning.

The final Fig. 6 illustrates the effect of the length of the resonator on the splitting of its resonance lines. The corrected spectra look similar to those in the original paper, albeit somewhat smoothed out, so that EIT-like pattern is not observed even at smaller values of L. We also note that while the splitting does become more pronounced with an increase in L as was discussed in the original paper, this may be considered an apparent effect resulting from different scales on the horizontal axes of different panels of Fig. 6. A careful look at the spectra shows the

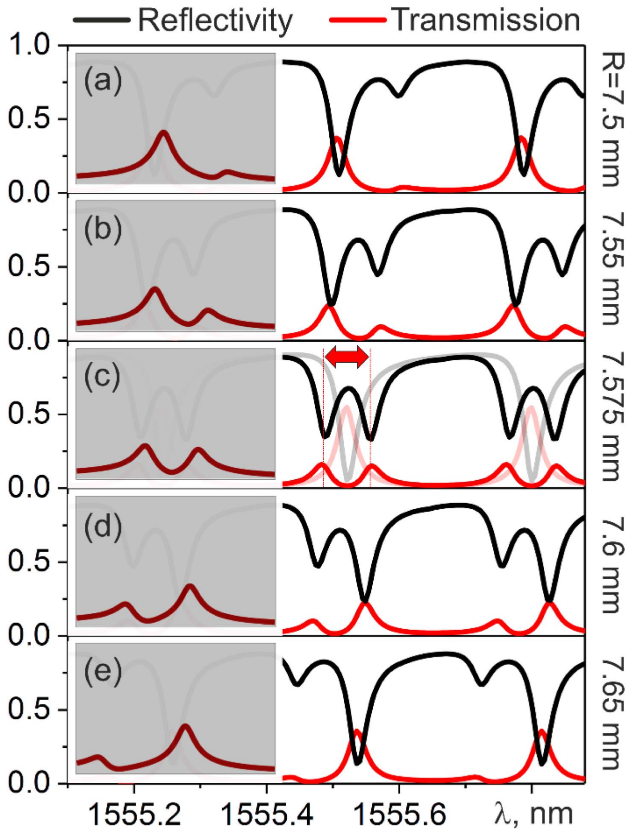

Fig. 3. Reflection and transmission spectra of the bent waveguide resonator calculated at $R = 7.5$, 7.55, 7.575, 7.6 and 7.65 mm, $L = 3$ mm, $\text{th}_m = 10$ nm. Shown for comparison with semi-transparent lines are the spectra of the corresponding straight resonator. The grey insets to the left depict the corresponding frequency response of the driven oscillator in the coupled pendulum system [Fig. 2(b)] obtained with $\omega_1 = 1$, $\omega_2 = 1.2$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.25$ (a); $\omega_1 = 1$, $\omega_2 = 1.07$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.25$ (b), $\omega_1 = 1$, $\omega_2 = 0.98$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.25$ (c); $\omega_1 = 1$, $\omega_2 = 0.85$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.25$ (d); $\omega_1 = 1$, $\omega_2 = 0.7$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.25$ (e).

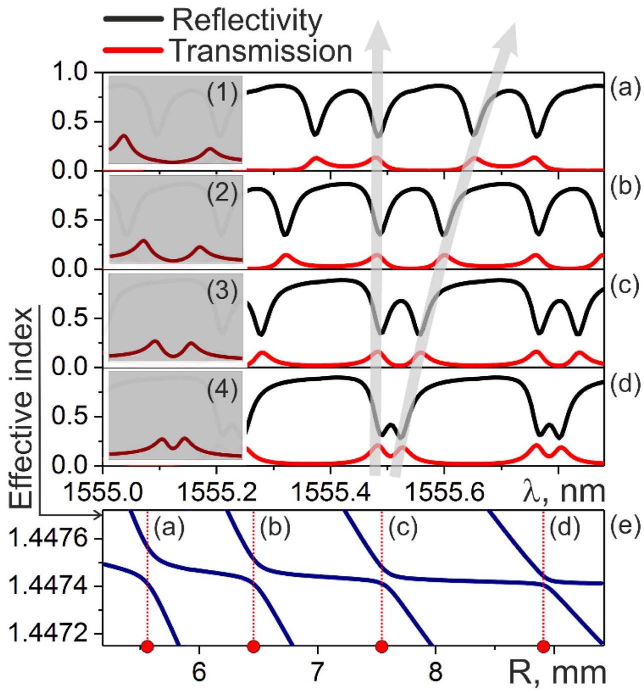

Fig. 4. Reflection and transmission spectra of the bent waveguide resonator calculated at $R = 5.575$ (a), 6.475 (b), 7.575 (c) and 8.932 mm (c), $L = 3$ mm, $\text{th}_m = 10$ nm and corresponding frequency response of the driven oscillator in the coupled pendulum system (Fig. 2b) obtained with $\omega_1 = 1$, $\omega_2 = 0.98$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.6$ (1); $\omega_1 = 1$, $\omega_2 = 0.98$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.4$ (2); $\omega_1 = 1$, $\omega_2 = 0.98$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.25$ (3); $\omega_1 = 1$, $\omega_2 = 0.98$, $\gamma_1 = \gamma_2 = 0.1$, $g = 0.15$ (4). Vertical semi-transparent arrows schematically indicate the widening of the resonance splitting with decreasing bend radius. Shown in (e) are the dependences of the bent waveguide supermodes effective indexes on the bend radius at a fixed wavelength of 1555 nm. Dashed red vertical lines denote the bend radii at which the spectra shown in (a)–(d) were obtained.

splitting to be virtually unchanged in absolute terms while the resonance lines become narrower and more closely spaced with increasing L thus making the splitting look more pronounced.

An interesting feature that was not mentioned in the original paper is observed at $L = 12.1$ mm when the resonant transmission is almost zeroed by the overlap of the split lines from two adjacent resonances, which is accompanied by a deep minimum in the reflection spectrum. The calculation of the intensity distribution in the bent resonator shows that almost all of the injected power goes, in this case, into the cladding of the output waveguide section.

All the simulation results presented in the original paper and in this erratum were obtained for TM polarization (with the electric field polarized in the plane of the bent waveguide). Calculations for the orthogonal polarization yield similar results albeit slightly shifted in wavelength due to the polarization dependence of WGMs effective indexes.

Summarizing the results presented above we must conclude that, contrary to what was erroneously stated in the original paper, the splitting of resonances of the considered bent waveguide resonator does not lead to narrow spectral features and sharp variations in the transmission and reflection spectra, characteristic of high Q-factor Fano resonances and electromagnetically induced transparency. Instead, a pattern very similar to the well-known Autler-Townes splitting is typically observed, corresponding to the coupling of two equally damped resonant states. This is actually what should be expected in the studied case of coupling between FM- and WGM-resonators, because their losses, defined primarily by the transmission through the input and output mirrors, are equal. It is for this reason that equal damping constants of the coupled pendulums in the parallel mechanical system [$\gamma_1 = \gamma_2$, Fig. 2(b) in the original paper] are required to match the corrected transmission spectra of the bent resonator with the frequency response of the driven pendulum (grey insets in the above Figs. 3 and 4).

Sharp asymmetric Fano and EIT-like line shapes, on the other hand, arise from the interference of a narrow resonant line with a nonresonant continuum or another broad resonance. In particular, to observe such effects in the mechanical system of two coupled pendulums the following condition must be satisfied: $\gamma_2 \ll \gamma_1$ [2]. Therefore, to enable high Q-factor Fano

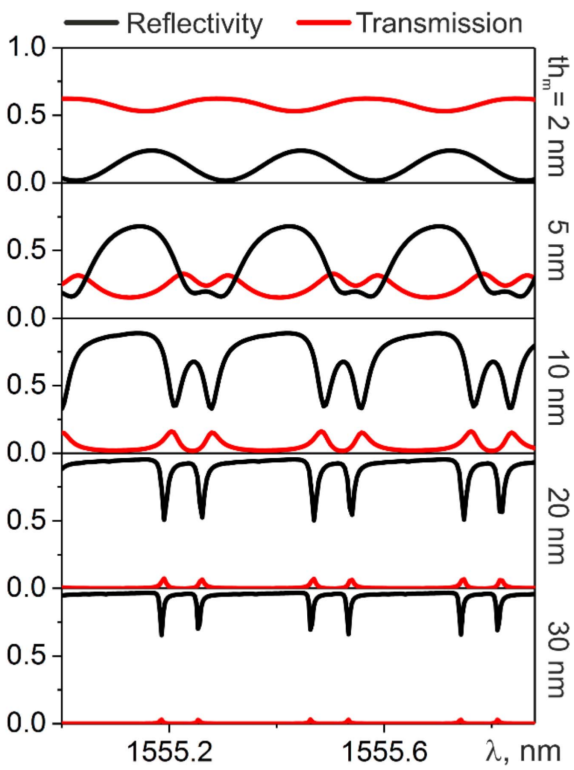

Fig. 5. Reflection and transmission spectra of the bent waveguide resonator calculated at $\text{th}_m = 2, 5, 10, 20$, and 30 nm, $R = 7.575$ mm, and $L = 3$ mm.

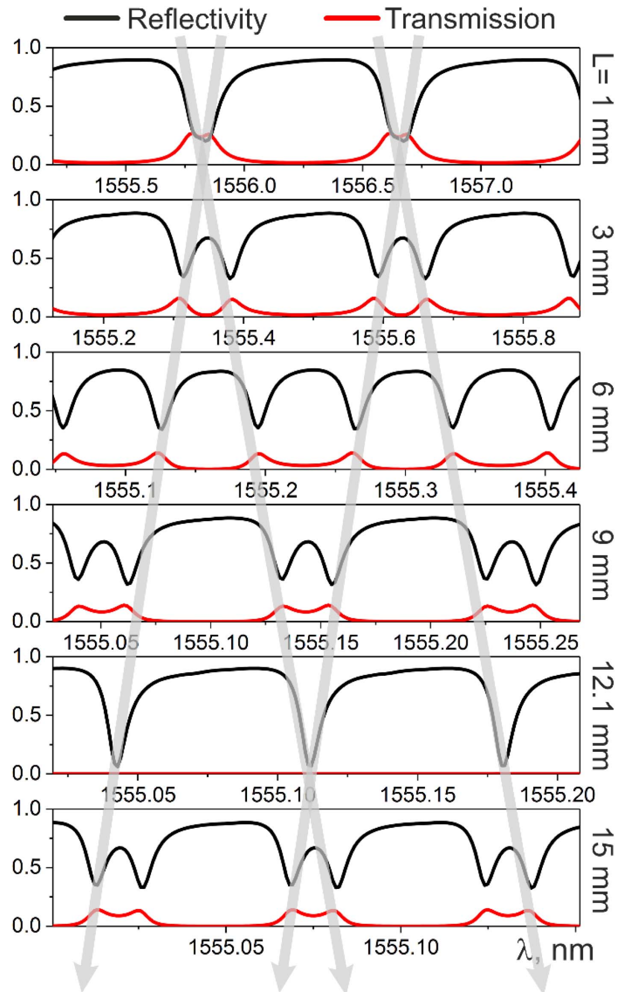

Fig. 6. Reflection and transmission spectra of the bent waveguide resonator calculated at $L = 1$, 3, 6, 9, 12.1 and 15 mm, $R = 7.575$ mm, $\text{th}_m = 10$ nm. With vertical semi-transparent arrows we illustrate the displacement of the split resonance lines as the length of the resonator changes.

resonance and EIT-like operation regimes in the bent waveguide Fabry-Perot resonator (which are more attractive in terms of the design of sensing and switching photonic devices), variable transmission mirrors must be employed providing low losses for the WGM-resonator and high losses for the FM-resonator. Results of further research in this direction will be published elsewhere.

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