Magnesium Fluoride Microdisk Resonators for Frequency-Dependent Squeezing via Einstein–Podolsky–Rosen Entanglement

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Abstract: We demonstrate a platform for generating bipartite entangled quantum frequency combs using magnesium fluoride microdisk resonators with high Q factors. The system supports 14 continuous-variable quantum modes, with the frequency-dependent squeezing state being finely adjustable.

1. Introduction

Multimode squeezed light in optical quantum states is crucial for advancing quantum information technologies, such as communication, computation, and metrology [1]. Some studies use the two-mode squeezed vacuum state to adjust the squeezing angle, replacing costly and hard-to-implement filters [2, 3]. Magnesium fluoride (MgF_2) microdisk resonators, with an exceptionally high Q factor on the order of 10^9, provide a platform for generating EPR-entangled quantum states that exhibit strong frequency dependence. These resonators, characterized by low energy dissipation and high stability, enable precise manipulation of quantum frequency combs and the generation of frequency-dependent squeezed states.

We introduce a platform [4] based on magnesium fluoride microdisk resonators, which provides precise dispersion and coupling control [5]. Serving as a resource for generating EPR entangled states,this platform generates frequency-dependent squeezed states with at least 14 channels, each yielding frequency-dependent single-mode squeezed states. The high Q factor of the resonators, on the order of 10^8 to 10^9, ensures stability, while the flexibility of the gap enables significant adjustability of the coupling rate r. This system opens up new possibilities for the use of quantum squeezed states in quantum metrology, communication and computation.

2. Simulation Model of Microdisk Resonators

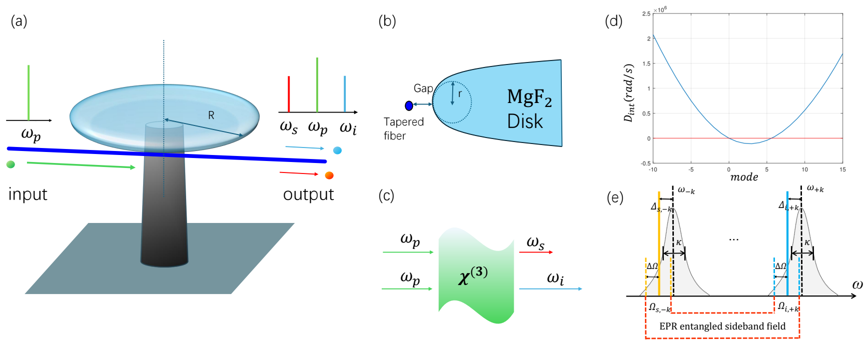

Fig. 1. (a) A three-dimensional illustration. (b) A partial side view of (a). (c) A schematic depiction of FWM process. (d) The simulation result of $D_{\rm int}$.(e) The relative positions of signal and idler bands in EPR-entanglement.

We employ COMSOL Multiphysics to model the waveguide's geometry and integrated dispersion profile. A fifth-order polynomial fitting extracts parameters matching the integrated dispersion $D_{\rm int}$ (Fig. 1).After choosing the instinct $Q_0 = 5\times10^9$, We compute the coupling rate $\mu = 1.215\times10^5$. For other parameters, we have radius $R = 2.75$mm, simulations yield mode 0 frequency $f_0 = 193.414$ THz, second-order dispersion coefficient $D_2 = 3.040\times2\pi\times10^4$ rad/s, and effective area $A_{\rm eff} = 368.34\,\mu{\rm m}^2$.

3. Analysis of Entanglement and Squeezing

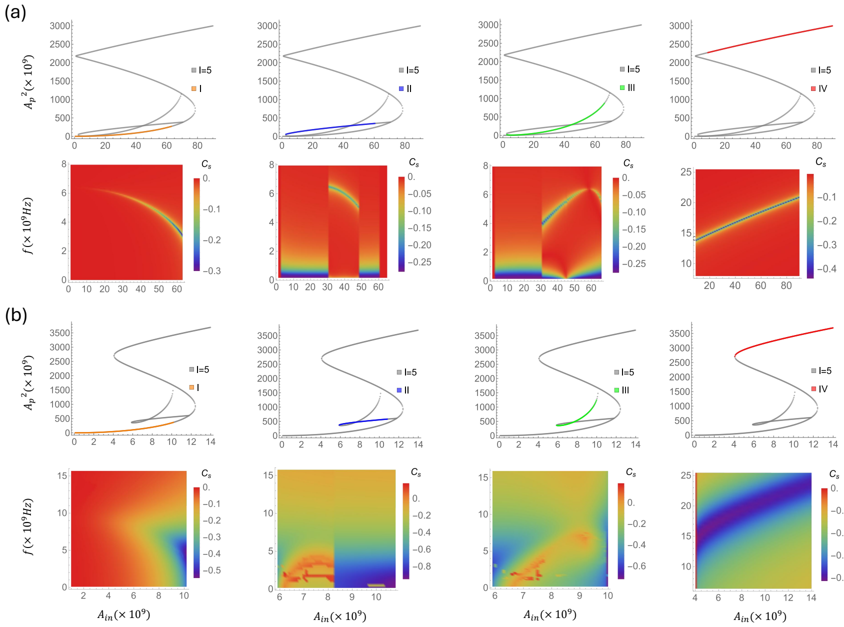

Fig. 2. The intracavity pump mode amplitude with respect to the injected pump amplitude A_{in} for the fifth mode, and the entanglement degree in the regime of A_{in} and observation frequency f with different coupling rate r.(a) $r = 1.222$, (b) $r = 99$. The discontinuous points in the figure are due to the scanning resolution.

To demonstrate, we select $l = 5$ from the seven available mode numbers as a representative example and divide the analysis into four distinct stages. The relationship between the entanglement degree C_s and the observation frequency f is examined. For each observation frequency, the optimal readout angle is determined accordingly. In addition, we find that as the coupling rate r increases, more of the entanglement within the cavity can be efficiently extracted into the tapered fiber, leading to a larger squeezing factor C_s, which is demonstrated in Fig.2.

4. Conclusion

In conclusion, we have developed a stable platform for generating EPR-entangled quantum frequency combs using a magnesium fluoride microdisk resonator with a high Q-factor and adjustable coupling rate r. Using one of the seven pairs of EPR-entangled, we generate a frequency-dependent single-mode squeezed state, enabling the investigation of the complex relationship between the degree of entanglement and the observation frequency. This approach provides valuable insights into frequency-dependent squeezing and demonstrates significant potential for advancing quantum precision measurement technologies.

This work was supported by the National Natural Science Foundation of China (Grant No. 62075129), the Open Project Program of the SJTU-Pinghu Institute of Intelligent Optoelectronics (No. 2022SPIOE204)

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