Photonic resonators with hybrid standing-traveling waves

Q. Zhong[1,2], H. Zhao[3], L. Feng[4], K. Busch[5,6], S.K. Ozdemir[7], R. El-Ganainy[1,2]
[1]*Department of Physics, Michigan Technological University, Houghton, MI 49931, USA*
[2]*Henes Center for Quantum Phenomena, Michigan Technological University, Houghton, MI 49931, USA*
[3]*Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA 19104, USA*
[4]*Department of Materials Science and Engineering, University of Pennsylvania, Philadelphia, PA 19104, USA*
[5]*Humboldt-Universität zu Berlin, Institut für Physik, AG Theoretische Optik & Photonik, 12489 Berlin, Germany*
[6]*Max-Born-Institut, Max-Born-Straße 2A, 12489 Berlin, Germany*
[7]*Department of Engineering Science and Mechanics, and Materials Research Institute, Pennsylvania State University, University Park, PA 16802, USA*

Abstract: We introduce a new class of photonic resonators with resonant modes that feature hybrid standing-travelling waves.

Optical resonators are structures that utilize wave interference and feedback to confine light [1-3]. Depending on the feedback mechanism, resonators can support either standing or traveling wave modes. Generally, traveling wave resonators, such as microring geometries, exhibit degeneracy between the counter propagating waves, and hence the eigenmodes can be also expressed in terms of standing waves by using appropriate bases. Today this classification of resonators as standing or traveling wave resonator is generally accepted as complete. In this work we show that this is not the case. Instead, we reveal a new type of optical resonator that represents a missing link between these two categories. Specifically, we propose a new resonator geometry that supports an optical mode exhibiting hybrid standing and traveling wave patterns simultaneously. This novel feature may have far-reaching consequences in building new devices with unique behavior.

To illustrate the generic concept of this hybrid-wave resonator, consider a resonator that can be divided into three domains: D_0, D_1 and D_2, as shown in Fig. 1. Furthermore, assume that it supports two degenerate, standing-wave modes $M_{1,2}$ such that field distribution of M_1 mainly resides in $D_0 \cup D_1$, and similarly the field associated with mode M_2 resides in $D_0 \cup D_2$. It may be anticipated that a superposition of these two degenerate modes can be constructed such that the standing wave nature of modes $M_{1,2}$ in domains $D_{1,2}$ remain unaltered and yet the field distribution in D_0 forms a traveling wave pattern due to a particular linear superposition of modes $M_{1,2}$. Such a "mutant" resonator will support a "mutant" optical mode that, in some properly chosen bases, exhibits purely standing- and traveling-wave patterns at the same time.

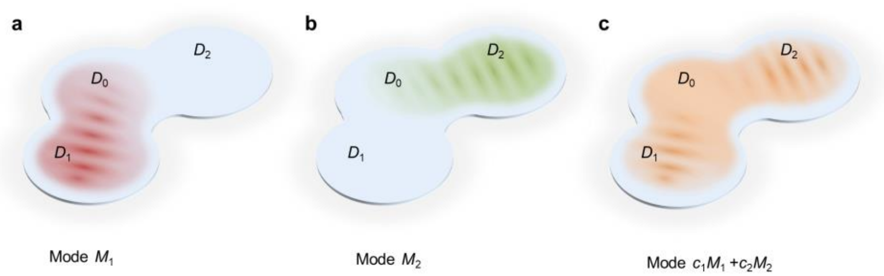

Fig. 1 A resonator that supports two degenerate standing-wave modes such that (a) mode M_1 resides in domain $D_0 \cup D_1$, and (b) mode M_2 resides in domain $D_0 \cup D_2$. (c) A proper linear superposition of M_1 and M_2 can result in new modes that preserve the standing wave character in domains $D_{1,2}$ while at the same time form a travelling wave in domain D_0.

To this end, let us consider the resonator geometry shown in Fig. 2, which consists of two mirror loops connected by a central section via two beam splitters. By using scattering matrix analysis [4,5], we find that the field amplitudes (indicated on the figure) of the optical modes are given by $[a_1, b_1, a_2, b_2, a_3, b_3, a_4, b_4] = \left[1,0,\frac{1}{\sqrt{2}}e^{i\frac{\phi m}{4}},\frac{i}{\sqrt{2}}e^{i\frac{3\phi m}{4}},0,ie^{i\frac{\phi m}{2}},\frac{-1}{\sqrt{2}}e^{i\frac{3\phi m}{4}},\frac{i}{\sqrt{2}}e^{i\frac{\phi m}{4}}\right]$ or $\left[0,1,\frac{i}{\sqrt{2}}e^{i\frac{\phi m}{4}},\frac{-1}{\sqrt{2}}e^{i\frac{3\phi m}{4}},ie^{i\frac{\phi m}{2}},0,\frac{i}{\sqrt{2}}e^{i\frac{3\phi m}{4}},\frac{1}{\sqrt{2}}e^{i\frac{\phi m}{4}}\right]$. Interestingly, these modes feature a purely traveling wave in domain $D_0 = D_0' \cup D_0''$, and at the same time a purely standing wave in domain D_1 and D_2.

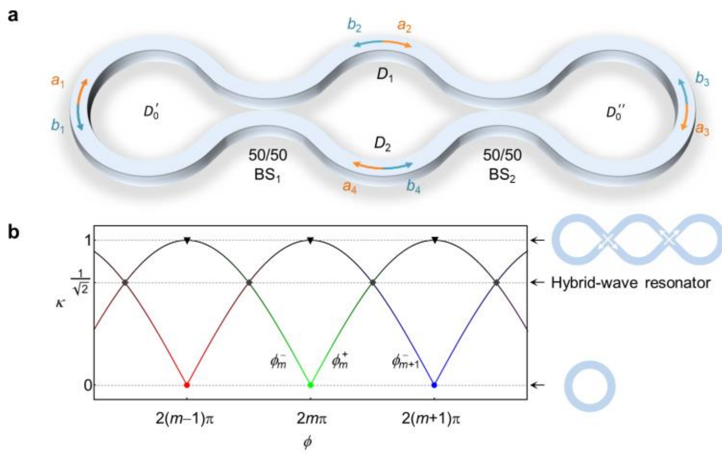

Fig. 2 (a) A hybrid-wave resonator can be constructed by deforming a ring resonator to introduce two 50/50 beam splitters, $BS_{1,2}$. The resonator can be divided into three domains: $D_0 = D_0' \cup D_0''$, D_1 and D_2. The field amplitudes at each location are labeled as a_i and b_i, $i = 1,2,3,4$. (b) Resonant frequencies (horizontal axis) as a function of the beam splitter coupling coefficient κ (vertical axis). Hybrid-wave modes exist for $\kappa = 1/\sqrt{2}$.

To verify the above predictions, we perform a finite element method (FEM) simulation of a realistic implementation. As shown in Fig. 3, standing wave patterns at the central section are visible through their interference pattern, while traveling waves on both edges are characterized by uniform fields distribution without any interference fringes.

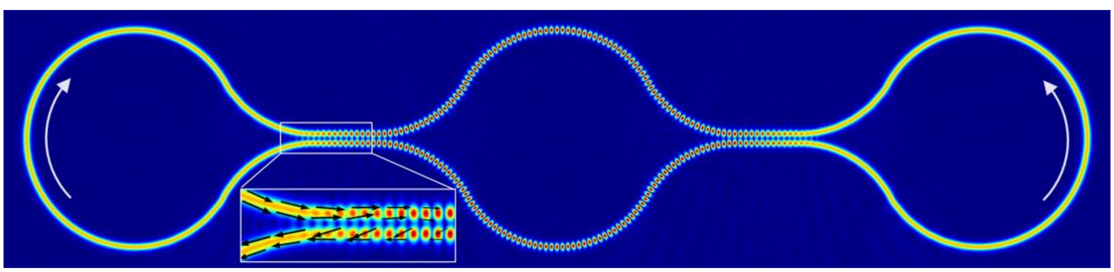

Fig. 3 Eigenmode of a hybrid-wave resonator. The white arrows indicate the traveling direction of traveling wave, while the black arrows indicate the direction and magnitude of Poynting vectors.

In conclusion, we have demonstrated a new concept for optical resonators that exhibit simultaneously co-existing standing and traveling waves as part of the field distribution of the same optical mode but occupying different locations along the resonator geometry. In addition, we have verified our predictions by using full-wave simulations for a structure made of ring-type resonators.

References

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