ELECTROMAGNETIC ENERGY TRANSPORT ABOVE AND BELOW THE DIFFRACTION LIMIT IN MESOSCALE COUPLED-CAVITY PHOTONIC AND PLASMONIC WAVEGUIDES

S. V. Boriskina [1], S. V. Pishko [1], T. M. Benson [2], P. Sewell [2]

[1] V. Karazin Kharkov National University, School of Radiophysics, 4 Svobody Sq., 61077, Kharkov, Ukraine
[2] University of Nottingham, School of Electrical and Electronic Engineering, NG7 2RD, Nottingham, UK
SBoriskina@gmail.com

Abstract – **We present a detailed and rigorous analysis of finite-size coupled-cavity optical waveguides (CCWs) - practical elements with tunable characteristics that enable guiding, routing, slowing and storing light. We discuss recent advances in design, fabrication, and applications of such structures and study mode coupling and guiding mechanisms in straight and curved CCW sections composed of optical cavities with sizes above, on and below optical wavelength. Possible ways to reduce or compensate radiation and absorption losses are proposed. These include optimal tuning of the waveguide bend geometry and exploring new classes of hybrid photonic-plasmonic mesoscale guiding structures. Application of plasmonic nanocavity arrays as optical-microcavity-coupled end-structures for focusing and channelling optical energy to single atoms, molecules, and nano-emitters is also discussed.**

I. INTRODUCTION

Technological advances of recent years resulted in rapid shrinking of devices for confining, controlling, and routing electromagnetic fields to the scale of the optical wavelength. Among the most essential building blocks employed in such devices to achieve the needed circuit functionality are dielectric and semiconductor optical microcavities (MCs), which enable efficient light trapping in the cavity volume and enhanced light-matter interaction [1]. Using the interaction of light with surface plasmons (SP) in noble-metal nanocavities (NCs) makes possible even further miniaturization of the photonic circuits to the sub-wavelength scale [2]. Complex structures composed of coupled cavities (see Fig. 1 for CCW examples) demonstrate fascinating optical properties that can be easily tuned by adjusting individual cavities size, shape and coupling distance. Such structures open amazing opportunities in a wide range of areas including data storage, near-field imaging, bio(chemical)sensing, non-linear optics, and material science. We will review the applications of coupled-cavity chains for energy transport and routing above and below the diffraction limit in various types of coupled-cavity waveguides, compare approximate and advanced simulation methods proposed to study CCW optical characteristics, and discuss possible strategies for minimizing radiation and absorption losses in such structures.

II. ANALYTICAL FORMULATION AND NUMERICAL ALGORITHM

A comprehensive numerical study of 2-D coupled-cavity structures to be presented is performed based on a rigorous spurious-solution-free Muller boundary integral equations (MBIEs) formulation [3]. This formulation reduces the problem from 2-D to 1-D (thus drastically reducing the numerical effort), automatically imposes the radiation condition at infinity, and enables treating both high and low index-contrast materials with material losses and gain. It also makes possible studying surface plasmon resonances in nano-cavities made of noble metals. Unlike conventional numerical techniques used for CCW simulations (such as ray-tracing methods, coupled-mode theory, tight-binding and coupled-dipole approximations) the MBIEs-based algorithms provide a powerful tool for modeling CCWs with size and coupling distance disorder, bent waveguide sections where strong evanescent-field coupling may occur not only between the neighboring cavities in a chain, and hybrid CCWs structures composed of cavities with varying material and geometrical characteristics.

III. CCW SPECTRA AND MINIMIZATION OF BEND LOSSES

First, the developed algorithms will be used to study transmission spectra of finite-length CCWs composed of whispering-gallery (WG) mode microdisk resonators (Fig. 2). In Fig. 2, sharp minima correspond to the frequencies of the coupled-cavity WG-supermodes, at which efficient light transmission along the chain can occur. Clearly, the increase of the number of coupled cavities leads to appearance of additional dips, which eventually transform into a broad unstructured band in the spectrum of an infinite CCW. Next, transmission characteristics of curved CCW sections will be studied with the aim to identify general design rules for realizing low-less bends in waveguides composed of cavities with sizes above, on, and below the optical wavelength (Figs. 3,4). The effect of tuning the cavity sizes, airgap widths, bend angles, etc. on CCW bend losses will be demonstrated. We will also explore ways to reduce the computational complexity of the algorithms while retaining the high accuracy of numerical solution by neglecting the interactions between widely spaced cavities.

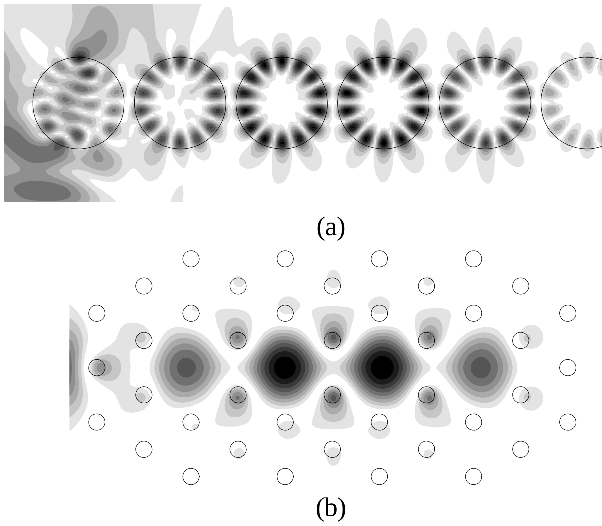

Fig. 1. Electric field intensity portraits in CCWs composed of (a) side-coupled microdisks (r = 0.9 µm, ε = 7, d(airgap) = 0.2 µm) and (b) point-defect photonic crystal cavities (r = 0.6 µm, d = 2.8 µm, ε = 8.41). The waveguides are fed from left by a complex-point source beam [3].

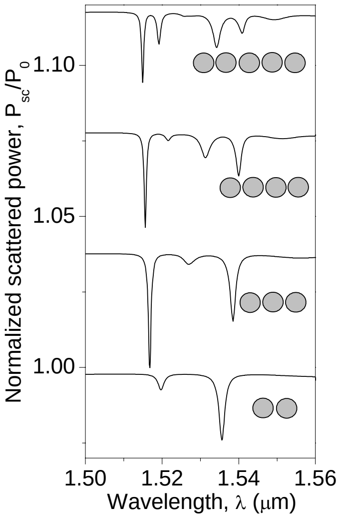

Fig. 2. Scattering spectra of a straight finite-size CCW section for varying numbers of coupled disks with the same parameters as in Fig. 1a.

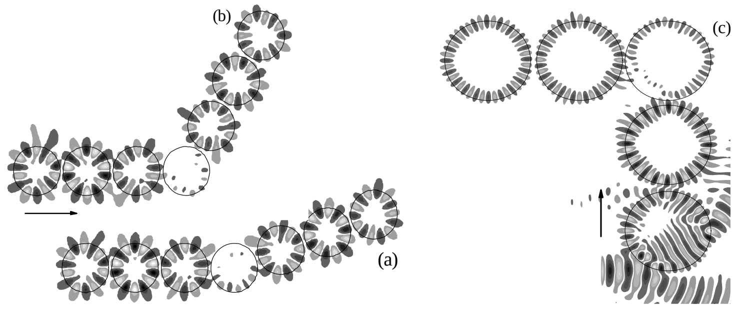

Fig. 3. Coupled-WG-mode electric field intensity distributions in bent chains of (a) wavelength-scale microdisks of high index contrast (r = 0.9 µm, ε = 7) and (b) optically-large resonators of low index contrast (r = 3.65 µm, ε = 2.5) at λ ~ 1.55 µm. The CCWs are excited by a directional beam generated by a complex-point source [3]. Here and in Fig. 4 the arrows show the direction of light propagation along the CCWs.

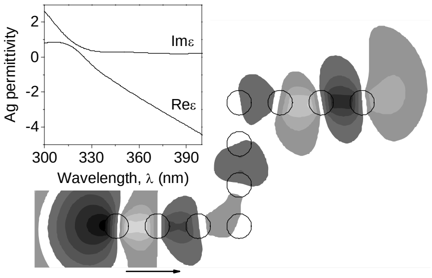

Fig. 4. Magnetic field distribution in an SP resonance along a bent chain of coupled Ag nano-wires with radii of 30 nm and inter-wire spacing of 40 nm at λ = 365 nm. The inset shows the real and imaginary parts of the dielectric constant for silver as a function of wavelength.

V. HYBRID MESOSCALE PHOTONIC-PLASMONIC CIRCUITS

CCWs composed of noble-metal plasmonic nanocavities make possible channelling and concentrating light in dimensions much lower than the diffraction limit (Fig. 4). A serious limitation to the applicability of plasmonic NC structures is their high propagation loss due to resistive heating losses of metallic structures, and difficulty of efficiently coupling light in and out of the metal NC structures using conventional optoelectronic input and output couplers. Thus, there always is a trade-off between tight energy confinement and high loss of plasmonic NC structures that imposes strict constraints on the functionality of plasmonic devices and circuits. There exist however theoretical and experimental evidence that the absorption losses in metal can be compensated by gain in surrounding dielectric or semiconductor medium, which paves the way to a broad spectrum of exciting practical applications of plasmonic coupled-nanocavity structures. To this end, we plan to explore the opportunities that can emerge through convergence of strong sub-wavelength field confinement offered by plasmonic nanocavities with optical gain medium and record Q-factors achieved in optical WG-mode microcavities. Such convergence is expected to result in the development of new classes of mesoscale photonic devices for optical energy transport, routing, and channelling to single particles or nano-emitters. However, to achieve the desired functionality of such hybrid devices, both micro- and nano-scale cavities have to be spectrally and geometrically engineered to maximize spatial and spectral overlap between their respective modal fields (Fig. 5).

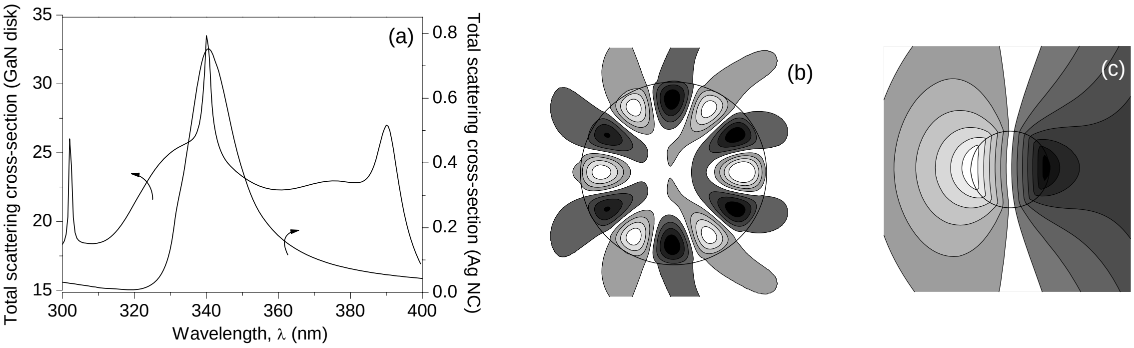

Fig. 5. (a) Plane-wave scattering spectra of a GaN microdisk resonator (r = 222 nm, ε = 5.34) and an SP Ag nanowire (r = 15 nm). Geometrical parameters of both cavities are tuned to achieve the spectral overlap of a WG-mode resonance in the microdisk with a dipole SP resonance in the nanowire. (b,c) Magnetic near-field portraits in the corresponding resonances.

VI. CONCLUSIONS

Using the MBIEs formalism for the description of optical modal fields in finite-size chains of coupled 2-D MCs and NCs of arbitrary configuration, we demonstrate the power of this technique to reveal a detailed picture of CCW modal spectra and field profiles, and thus to offer design strategies for controlled manipulation of their transmission characteristics. Furthermore, we propose to combine record Q-factors achieved in optical MCs with exceptionally strong sub-wavelength field confinement observed in plasmonic NCs to develop new classes of the hybrid photonic-plasmonic devices. Here, the main challenges will be to design the individual micro- and nano-sized building blocks needed to achieve the desired functionality, and to bridge the gap between the nano- and the micro- worlds by modelling the interactions between NCs and MCs. The developed MBIEs technique will serve as a powerful tool enabling us to achieve this ambitious goal. The computed optical characteristics of 2-D CCWs will be compared with the available experimental data and the results of 3-D simulations.

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