

# Subwavelength light guiding in photonic funnels

Alexander A. Goyadinov and Viktor A. Podolskiy\*

Department of Physics, Oregon State University, 301 Weniger Hall, Corvallis, OR 97331

\*e-mail: viktor.podolskiy@physics.oregonstate.edu

**Abstract:** We present new class of waveguides with metamaterial cores. In contrast to conventional structures, our system propagates light on subwavelength scale and provides effective nano-to-micro coupling. The design is scalable from optical to THz frequencies.

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Compressing the light beyond the diffraction limit is one of the most fundamental problems of modern photonics and plasmonics. Effective coupling between diffraction-limited and sub-diffraction scales will strongly benefit the areas of near-field sensing, nm-scale optical control, single-molecule spectroscopy, high-energy focusing and compact optoelectronics [1-4]. Present solutions of this problem either rely on the evanescent coupling in tapered waveguides [5,6], or employ the propagation of surface waves [7-10]. In the latter case, non-trivial coupling, is required to excite *surface modes* [9,11]. Since the structure of the surface waves is fundamentally different from the one in free-space and in telecom fiber modes, such a coupling is typically accompanied with substantial energy loss [12]. Here we present a new class of waveguides with composite cores that support strongly confined light with mode structure similar to that of a conventional fiber. We demonstrate scalability of our approach from near-IR to mid-IR to far-IR frequencies, and show the energy compression to spatial areas as small as  $\lambda/40$ .

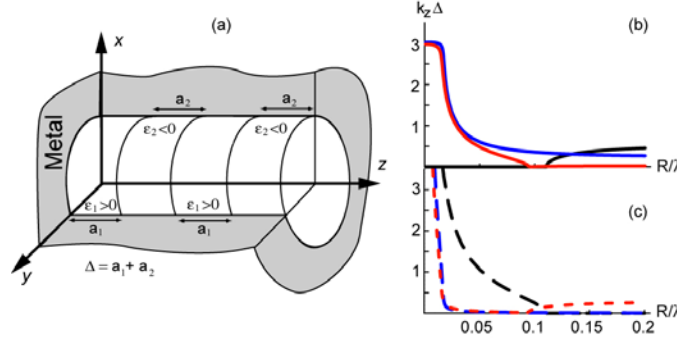


Fig. 1. The proposed PC waveguide (a). Normalized real (b) and imaginary (c) parts of the wavevector as functions of waveguide's radius. In black: typical dielectric waveguide or TE-wave; Positive (blue) and negative (red) index PC-cores.

Instead of using surface modes in "conventional" waveguide geometry we modify the properties of the waveguide itself, allowing the propagation of free-space-like waves in deep subwavelength regions. Specifically, we employ a 1D photonic crystal (PC) as a waveguide core. The mode propagation in the waveguide with such a metamaterial core is given by:

$$\cos(k_z \Delta) = \cos(k_1 a_1) \cos(k_2 a_2) - \gamma \sin(k_1 a_1) \sin(k_2 a_2) \quad (1)$$

$$\gamma_{TM} = \frac{k_1 \epsilon_2}{k_2 \epsilon_1} + \frac{k_2 \epsilon_1}{k_1 \epsilon_2}, \quad \gamma_{TE} = \frac{k_1}{k_2} + \frac{k_2}{k_1} \quad (2)$$

where  $\Delta$  is a period of PC structure,  $k_{1,2}^2 = \epsilon_{1,2} \omega^2 / c^2 - \kappa^2$ ,  $k_z$  is the mode-specific propagation constant, and parameter  $\kappa$  describes the mode structure across the waveguide [12]. In this work we concentrate on the case of substantially thin layers ( $\Delta \ll \lambda$ ). In this particular case the response of a PC system is similar to the one of strongly anisotropic optical material [13,14] with its optical axis parallel to  $z$ , and the Eq.(1) reduces to the effective-medium result:

$$k_z^2 = \epsilon v \frac{\omega^2}{c^2} \quad (3)$$

with parameters  $\epsilon$  and  $v$  (for TM wave) [15]:

$$\varepsilon_{TM} = \frac{a_1 \varepsilon_1 + a_2 \varepsilon_2}{a_1 + a_2} \quad v_{TM} = 1 - \frac{a_1 \varepsilon_2 + a_2 \varepsilon_1}{\varepsilon_1 \varepsilon_2 (a_1 + a_2)} \frac{\kappa^2 c^2}{R^2 \omega^2} \quad (4)$$

This is in turn similar to the dispersion relation of recently proposed anisotropic planar waveguides with negative refractive index [13,14]. Similar to the majority of metamaterials with internal structure at deep subwavelength scale, our design is expected to be highly tolerable to fabrication imperfections [see 14,18 and references therein].

Dispersion diagram of presented here waveguides with PC cores are shown in Fig. 1. It is clearly seen from it, that TM wave can propagate in the regions  $R \ll \lambda$ . We note however, that the spatial dispersion, implicitly present in any composite structure, leads to the TM mode cut-off when  $k_z \Delta \sim 1$ .

We demonstrate the perspectives of our design on examples of three realistic PC-based *photonic funnels*, designed for near- mid- and far-IR frequencies respectively. In our numerical simulations we represented the conical structures as an array of concentric cylinders with gradually decreasing radius and metallic walls. The field in each cylinder was represented as a series of *analytically calculated* waveguide modes, the mode matching technique described in details in [15] was used to find the solution of Maxwell equations across the system.

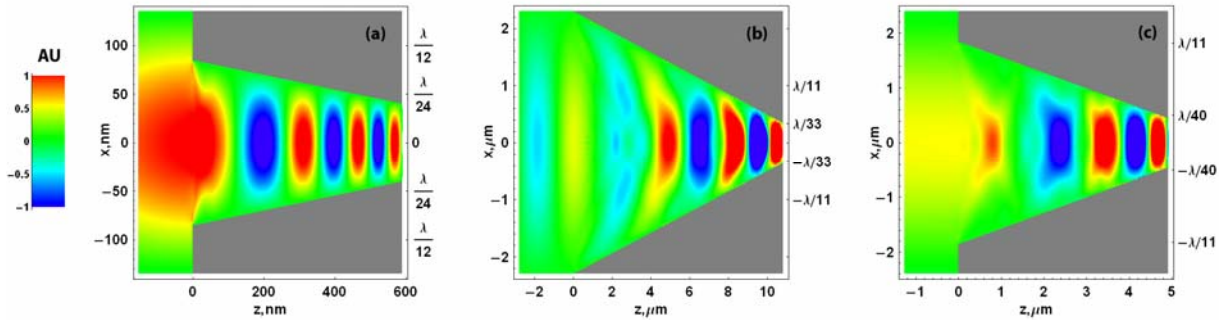


Fig. 2. Field distribution in photonic funnels. Real part of  $D_z$  in Si-Ag (a), Si-SiC (b) and AlInAs-AlGaAs with moderate gain (c) is shown.  $z > 0$  is occupied by PC-core,  $z < 0$  – represents Si (a and b) and AlInAs (c) "feeding" structure.

The wave propagation in photonic funnels with PC cores based on (i) 15nm-thick layers of Si and Ag, (ii) 100nm-thick Si and SiC layers, and (iii) 75 nm-thick InGaAs layers doped with electrons to  $10^{19} \text{ cm}^{-3}$ , and 150 nm AlInAs barriers is shown in Fig.2. The systems are designed for  $\lambda=1.2\text{mkm}$ ,  $1\text{mkm}$ , and  $20\text{mkm}$  respectively, and achieve the compression of radiation to  $\sim\lambda/26$ ,  $\lambda/31$  and  $\lambda/44$  regions.

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