Guiding light at criticality and beyond

Janderson R. Rodrigues*, Utsav D. Dave¸ Aseema Mohanty¸ Xingchen Ji, Ipshita Datta, Ricardo Gutierrez-Jauregui, Vilson R. Almeida, Ana Ansejo-Garcia, Michal Lipson
Department of Electrical Engineering, Columbia University, New York, New York 10027, USA
Department of Physics, Columbia University, New York, New York 10027, USA
jr3920@columbia.edu

Abstract: We experimentally demonstrate waveguiding at the critical angle in a dielectric multi-layered structure. At this exceptional point, the waveguide becomes scale invariant and the field is confined to the low-index region, with a spatially-uniform transverse profile.

Recently, non-Hermitian physics in photonic devices have attracted a lot of attention. The possibility of undergoing a phase transitions at the exceptional points have created extra degrees of freedom, where the imaginary part of the dielectric permittivity, associated with optical loss or gain, has expended the photonic domain to the complex plane [1].

Here, we show a novel lossless dielectric waveguide based on the interplay between real (guided) and imaginary (radiation) modes in dielectric waveguides. The new waveguide shows unusual properties including the guiding in the low index medium which, in contrast to the sub-wavelength slot waveguide [2], can be several wavelengths in dimension and works for both TE/TM polarizations. The guiding mechanism is associated with non-Hermitian physics, without creating propagation losses or making use of gain materials. To illustrate our findings, we consider the (five-layers) dielectric slab waveguide composed of two high-refractive-index materials (n_H), each one with a thickness t_H, separated by a low-refractive-index material (n_S) of thickness t_S, and immersed in a semi-infinite low-refractive-index material (n_C), where we assume $n_H > n_S > n_C$ and the guides modes are inside the interval $n_S < n_{eff} < n_H$, where n_{eff} is the mode effective index.

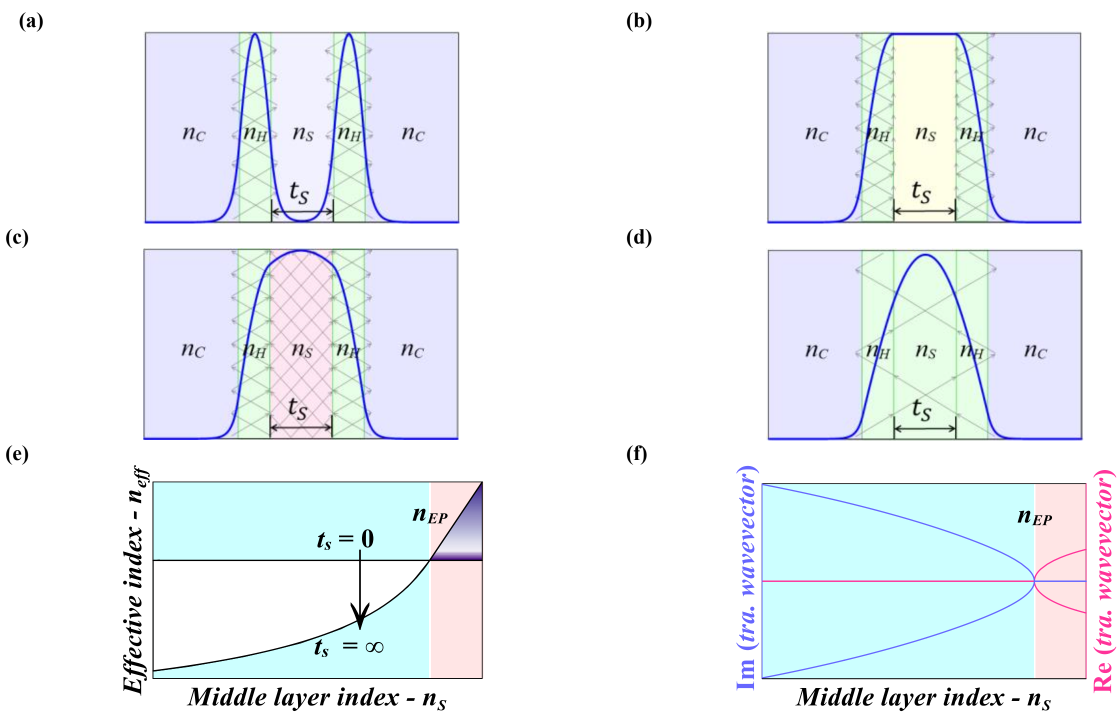

Figure 1. **(a-d)** Schematic of the ray-optics pictures and electromagnetic spatial distribution of the electric field intensities ($|E|^2$), for fundamental TE mode. **(a)** For $n_S = n_C$, the angle of incidence is above the critical angle at the inner interfaces creating the evanescent waves between the two waveguides with exponential fields decay. **(b)** At $n_S = n_{EP}$, the angle of incidence is equal to the critical angle, and the refractive waves travel at the interfaces. **(c)** When $n_S > n_{EP}$ the angle of incidence below the critical angle, there are reflection and refraction on both sides of the interfaces trapping the waves through solely the outer interfaces. **(d)** For $n_S = n_H$, it recovers the single wider waveguide. **(e)** Effective index as a function of the middle layer index for different thickness t_S showing the degeneracy (i.e. scale invariance) at the exceptional point. **(f)** Bifurcation diagram showing the phase transition of the transversal wavevector at the exceptional point.

For $n_S = n_C$ the optical mode has an (evanescent) exponential decay inside the middle layer, as shown in Fig. 1 (a). By increasing n_S above n_C, the evanescent field starts to increase until it reaches an exceptional point $n_S = n_{EP}$, where the electric field is perfectly uniform inside the middle layer, as presented in Fig. 1(b). The exceptional point coincides with the effective index of the mode when the thickness of the middle layer is zero ($t_S = 0$); therefore, at this point, the system losses dimensionality, and the optical mode presents translational invariance. This behavior is represented by a constant effective index (n_{eff}), as illustrated in Fig. 1(e). Figure 1(f) shows the bifurcation diagram formed by the transverse wavevector as a function of the middle layer index, where the exceptional point is at the transition between the real and the imaginary part. Furthermore, when $n_S > n_{EP}$, the mode becomes an internal radiation mode, where most of the light is confined in the lower index material, as presented in Fig 1(c). When $n_S = n_H$, the waveguide is now a thicker single waveguide, as shown in Fig. 1(d). By applying ray-optical concepts, we show that the exceptional point corresponds exactly to the critical angle between the two waveguides and middle layer; thus allowing for the refracted waves to propagate at the interface between two media. The result is consistent with our previous electromagnetic analysis shown in Fig. 1(b) where the decay length of the field diverges to infinity. Furthermore, after the exceptional point the angle of incidence is below the critical angle, avoiding the total internal reflection; therefore, the refracted waves are trapped between the two outer interfaces of the waveguide, as shown in Fig. 1(c).

To demonstrate the proposed effect, we fabricate a vertical stack composed of two silicon nitride SIN layers ($n_H \cong 2.0$) separated by a silicon oxynitride layer ($n_S \cong 1.75$), as shown in the inset of Fig. 2 (a). The width of the waveguide w is chosen to be 1μm, while the thickness of the silicon nitride layer, $t_H = 220nm$, is designed to have the predicted behavior near the telecom wavelength (λ_0 =1.55 μm) for the TE fundamental mode. We also fabricated pure SIN waveguides ($n_S = n_H$), to contrast with the proposed device. In order to measure the effective index, we use the approach described in [3]. A microscope image of one of the MZI interferometer devices is presented in Fig. 2(a), as well as one of the measured spectra with its fitting curve by using the Least Square regression method. Figure 2(b) shows the effective index behavior for five different values of the middle layer thickness, measured at the wavelength 1.545 μm. The results show that, in contrast to the conventional waveguide, the effective index of the novel waveguide stays practically constant. The FDTD simulations show the invariance of the electromagnetic intensity profile, in contrast with the usual Gaussian-like profile observed in conventional waveguides. For larger wavelengths, or thinner silicon nitride layers, most of the light will be confined in the low index material presenting a new way of confining light to the low-index material.

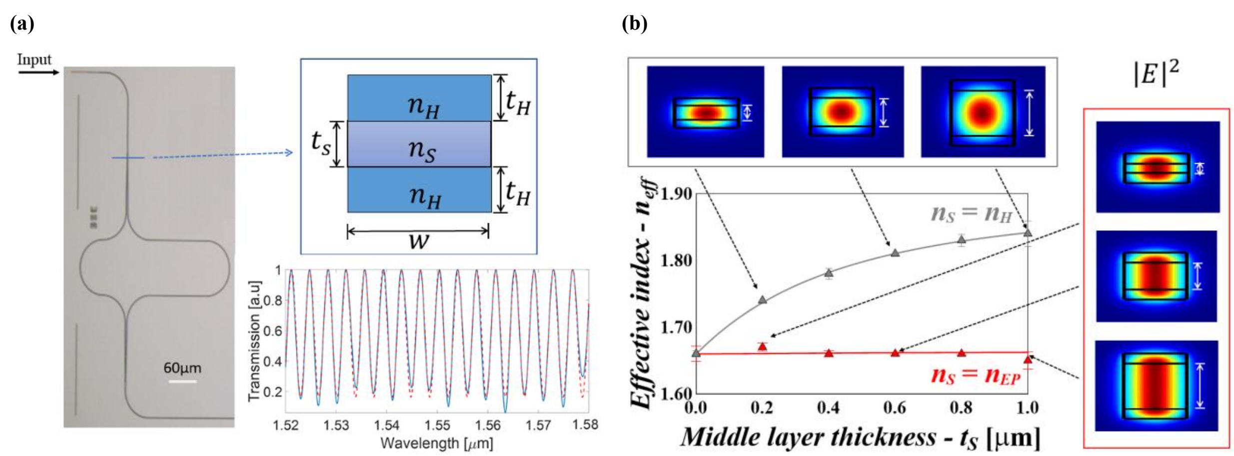

Figure 2. **(a)** Waveguide geometry: two high-index materials with index n_H and thickness t_H are separated by a low-index material with refractive index n_S and thickness t_S. Optical microscope image showing one of the MZI used to measure the effective index and one example of the measured spectra showing the experimental transmission and fitting curve. **(b)** Experimental (triangles) and simulation (solid lines) of the effective index n_{eff} as a function of the middle layer thickness for the two situations discussed previously. FDTD simulation of intensity spatial distribution as a function of middle layer thicknesses t_S for each case.

References

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