Control of light in the non-adiabatic regime in integrated optical waveguides

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ABSTRACT

We demonstrate that coupled waveguides systems can be operated in the so called non-adiabatic regime. In this regime, light can undergo transition between different steady states, also called photonic bands. This approach contrasts with previous strategies in integrated photonics that rely exclusively on the adiabatic control of the flow of light. We show that the constraint for adiabaticity being lifted, light can now be manipulated optimally.

Keywords: Integrated Photonics, Waveguides Array, Non-adiabatic Control, Photonic circuits design.

The ever-increasing use of integrated photonics for application and fundamental research is motivating the search for new design strategies, so that optical phenomena can be controlled - or observed- more easily. The intensive use of computer optimization in photonics does not provide much insight into new principles and properties of light manipulation, hence it is limited in adaptability and scalability of the solutions. Here we propose a framework that relies on fundamental properties of coupled waveguides systems, so that interpretable and optimal solutions for the manipulation of light can be obtained. Analogies between quantum physics and optics have given rise to many useful applications and strategies in both domains [1]. In this work, we demonstrate the photonic equivalent to the quantum transition between two levels of energy; where light can be switched between stationary states in a waveguides array (Figure 1 (a)). Fundamental physics set asides, the framework we introduce allows also better control of the patway of light in a waveguides array.

Without loss of generality, let consider light propagation in two coupled waveguides where the coupling κ and propagation constants $\beta_{1,2}$ that can be tailored with a distance :

$$\frac{d}{dz}\begin{pmatrix}E_1(z)\\E_2(z)\end{pmatrix} = i\begin{pmatrix}\beta_1(z) & \kappa(z)\\ \kappa(z) & \beta_2(z)\end{pmatrix}\begin{pmatrix}E_1(z)\\E_2(z)\end{pmatrix} = iH(z)\begin{pmatrix}E_1(z)\\E_2(z)\end{pmatrix}. \tag{1}$$

Instead of solving directly eq.(1), the $H(z)$ operator can be diagonalized as:

$$H(z) = V(z)\lambda(z)V^{\dagger}(z) \tag{2}$$

And by performing this eigen-decomposition of the propagation matrix $H(z)$ we can translate eq.(1) to the reciprocal space $\tilde{E} = V^{\dagger}E$, where the evolution is then described in terms of the eigenmodes (aka supermodes) of the system:

$$\frac{d}{dz}\begin{pmatrix}\tilde{E}_1(z)\\ \tilde{E}_2(z)\end{pmatrix} = \left[iK(z) + \frac{dV^{\dagger}(z)}{dz}V(z)\right]\begin{pmatrix}\tilde{E}_1(z)\\ \tilde{E}_2(z)\end{pmatrix}. \tag{3}$$

Here the first term $K(z)$ contains only diagonal elements and simply represents natural dephasing (asynchronicity) of the supermodes, while the second one $\frac{dV^{\dagger}(z)}{dz}V(z)$ is an anti-symmetric operator that contains the actual properties of the coupled system. In brief, the diagonal components of this operator correspond to the Berry phase - a parameter reflecting the topological properties of the system [2]. Meanwhile the off-diagonal terms correspond to a transfer of energy between supermodes, namely a coupling between the photonic bands supported by the photonic system. By essence these terms control the non-trivial and the non-adiabatic evolution of the photonic system. Works dealing with arrays of waveguides rely on (1), and design rules imply to keep the $\frac{dV^{\dagger}(z)}{dz}V(z)$ contribution minimal, so to work in the so-called adiabatic regime [3]. Still we focus here on this intermodal-coupling term and we demonstrate that light can be perfectly controlled in this regime. Moreover an optimal excitation/control shape that would maximize the transfer of energy between the supermodes can be derived.

For example, given an arbitrary shape for the non-adiabatic coupling that we set here as $\frac{dV^{\dagger}(z)}{dz}V(z) = B\begin{pmatrix}0 & -1\\ 1 & 0\end{pmatrix}$, and we impose further the constraint $K(z) = C^{te}$, eq.(3) is now completely defined. Importantly, the geometrical parameters $\beta_1(z)$, $\beta_2(z)$,$\kappa(z)$ that governs the system are related to the operator in eq.(3) by a bijective transformation. Therefore the values of the former can be found quite easily, without relying on complex optimization algorithms. The solution found here is also guarantee to be optimal. Other design constraints could also be added to the problems at little extra computation cost. We see in Fig. 1(b) that a moderate and slow modulation of the coupling and waveguides parameters are enough to perform a non-adiabatic light transition. Indeed non-adiabaticity does not requires abrupt changes of the systems parameters, but can also be a cumulative phenomenon. Note that a redistribution of energy between the supermodes in the reciprocal space would consequentially trigger light transition in the direct space, hence in between waveguides, therefore this method is suitable for the design of complex photonic switches [4].

For the current demonstration we consider two coupled waveguides with initial parameters $\kappa_0 = 0.075\mu m^{-1}$, $\beta_{01} = 10.81\mu m^{-1}$ and $\beta_{02} = 10.73\mu m^{-1}$. If these parameters are kept constant, the light remains in a steady state both in direct and reciprocal spaces :the asynchronicity between the coupled waveguides prevent the light from switching (left panel of Fig. 1(b) displays propagation over $L = 200\mu m$). After solving eq.(3), an optimal shape of modulation is obtained, allowing to excite the opposite supermode. This is characterized by the fact that the light can now make transition back and forth between the waveguides, and the supermodes. The resulting optimal shape for the modulation strength of $B = 0.2\Delta K$ is presented in Fig. 1(b). We observe a periodic pattern which resembles (but not exactly equals to) a sinusoidal modulation with same periodicity for $\kappa(z)$ and $\beta(z)$. For the waveguides modulated with the optimal pattern, we observe an energy exchange and periodic excitation of the supermodes, and the consequent light transition between the waveguides in the direct space. The beating periodicity is controlled by the modulation strength, hence $Z_{per} = 2\pi/B$.

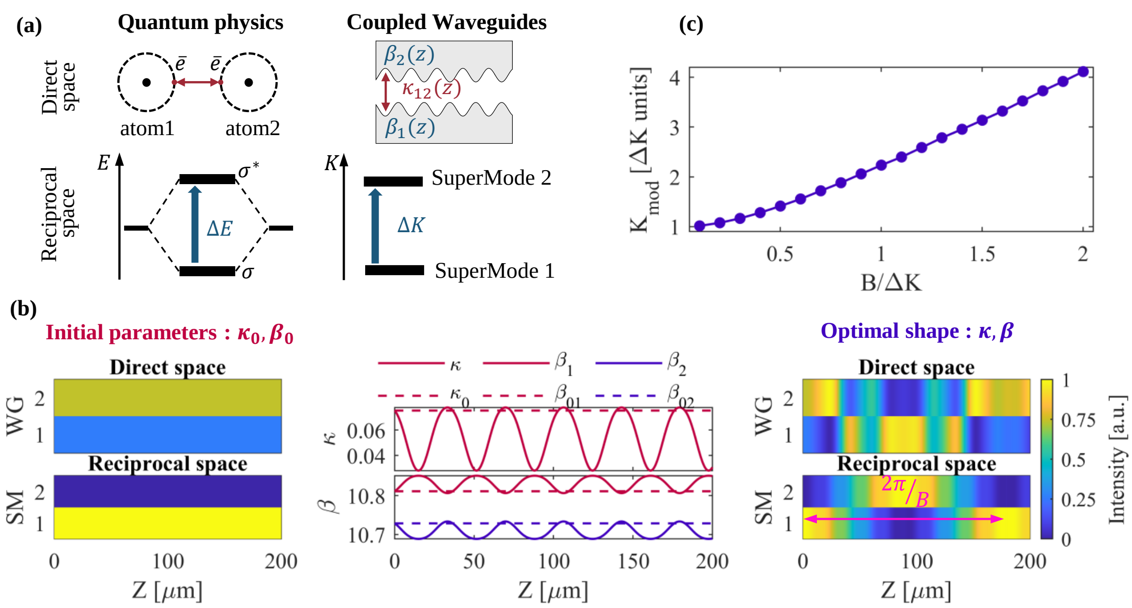

Figure 1: (a) Schematic analogy between optics and quantum mechanics. (b) Middle panels represent optimal shapes of the coupling κ $[\mu m^{-1}]$ and propagation constants β $[\mu m^{-1}]$ of waveguides 1 and 2 (full red and blue curves, respectively) for the modulation strength $B = 0.2\Delta K$, and comparison with initial constant parameters $\kappa_0 = 0.0754\mu m^{-1}$, $\beta_{01} = 10.8113\mu m^{-1}$ and $\beta_{02} = 10.7287\mu m^{-1}$ (dashed lines). Light propagation in direct and reciprocal spaces for constant and optimal parameters (left and right panels, respectively). (c) Frequency of the modulation pattern depending on the modulation strength B.

Considerations about momentum conservation indicate that indeed the non-adiabatic coupling must compensate the asynchronicity ΔK between the photonic bands, hence resulting in a periodic modulation. That said the case of non-adiabatic transition in coupled waveguides holds more complex dynamics. For instance, as illustrated in (Fig. 1(c), the patterns' periodicity with respect to the ratio $B/\Delta K$ (hence increasing non-adiabatic transfer rate) actually deviates notably from the nominal momentum conservation law. Such a feature can only made visible through the framework which we used here, hence the reciprocal (aka supermode) space representation. This example highlights the interest of the reciprocal space representation when it comes to the fine control of the properties in array of waveguides.

We demonstrated that arrays of integrated coupled waveguides can be operated in the non-adiabatic regime, which also gives a way to control these systems in the reciprocal space. With an optimal shape that is obtained from direct solving of a set of equations we can achieve efficient non-adiabatic light coupling; and consequently the adiabatic evolution restriction that was imposed thus far on the design of integrated photonic systems does not hold anymore. We believe this will open new opportunities in integrated photonics when it comes to the control of the flow of light on the chip.

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References

1. S. Longhi, “Quantum-optical analogies using photonic structures,” Laser & Photonics Rev. **3**, 243–261 (2009).
2. M. V. Berry, Proc. R.Soc. Lond. A (1984).
3. S.-Y. Tseng, “Robust coupled-waveguide devices usingshortcuts to adiabaticity,” Opt. Lett. **39** (2014).
4. A. Sheveleva, C. Finot, and P. Colman, “Dimensionality reduction for efficiency human and computer codesign in integrated photonics,” SPIE Integr. Photonics Platforms II, proceedings (2022).