

Photonic switching in waveguides using spatial concepts inspired by EIT

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Abstract: Optical waveguide switches based on spatial arrangements inspired by electromagnetic induced transparency (EIT) concepts are presented. Interferometric control of optical signal by an optical gate is accomplished in three configurations. The first is employing a direct spatial version of EIT, the second is exploiting space reciprocity to accomplish performance not achievable in the time domain EIT and finally a novel version of EIT, using tunneling, is transformed into the spatial domain. For all configurations – closed form analysis as well as actual device simulation are presented.

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References and links

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1. Introduction

A frequently used device in photonic circuitry for optical communications is the optical switch or modulator [1]. Classical technologies used for the implementations of a switch (and modulator) are based on interferometric techniques with a Mach Zender interferometer (MZI) [2] as the most prominent representative. The working principle of an MZI is splitting the optical input into two equal replicas (denoted here as signal and gate) – which are then interfered at the output – after the gate replica was subjected to a phase change. As such – an MZI is a two state apparatus, yielding different outcomes according to the relative phase values of the states. In a seemingly unrelated field – quantum interferometric schemes in atomic physics, are used to generate dark and bright quantum states, which are reminiscent of the on off switch states. These configurations – which are related to Electromagnetic Induced Transparency (EIT) [3] and similar phenomena, are based on coherent cancellation of the light absorption assisted by an additional light field (the coupling field) and a proper preparation (excitation) of the initial states. Due to remarkable similarity between Schrödinger and Maxwell equations [4], we were encouraged to use concepts related to quantum physics in the field of photonics, where energy levels and state wave-functions are replaced by the modal propagation constants and modal fields (respectively), and time evolution (perturbation) is replaced by spatial propagation (perturbation). As the EIT scheme is based on at least 3 atomic states, the new switching configurations proposed here are more elaborated than those relying on the classical two states MZI.

We took one step further and encountered also situations that are not feasible in the EIT framework – taking into advantage the reciprocity of the spatial domain vs. the forbidden time reversal. Finally – we exploited a novel EIT scheme – where the coupling field effect is replaced by a level splitting effect stemming from resonant tunneling [5] and proposed its spatial version as a switch without "external force" (gratings) namely a three waveguides coupler based switch. We would like to emphasize that we are not attempting here to tailor, by the spatial structure, a dispersion response that resembles that of atomic EIT, as reported before by employing periodic structures[6], coupled cavities[7] etc. We are just transforming the dynamics of the EIT quantum system to an equivalent propagation in waveguide structure, gaining interesting novel concepts for optical switching.

2. A switch based on Double-period gratings in a slab dielectric waveguide

A first spatial realization of the switch is based on the coherent variant of EIT, where the initial complex amplitude relations of the atomic states (state 1 and 2) are determining the absorption or transmission state of the probe field in the presence of the coupling field [Fig. 1(a)]. An equivalent waveguide switching device [Fig. 1(b)] will be constructed as follows: The optical input field is split (not equally) to signal and gate (usually lower amplitude) fields. These fields are fed as the input to two separated modes (1 and 2) of a waveguide (using mode coupler [8], not discussed here) which supports 3 modes (EIT configuration requires 3 states in an inverse lambda scheme). The launched modes propagate and evolve in the waveguide in an interaction region where two (temporarily stationary) long period gratings are imposed, with periods adjusted to couple modes 1-3 and 2-3 (structures equivalent to the two respective electromagnetic fields of the EIT scheme). Applying a proper phase change on the input gate field will result in a corresponding switching operation. A previous work in which a single optical output was switched by turning on and off transient gratings in a related structure was reported [9, 10].

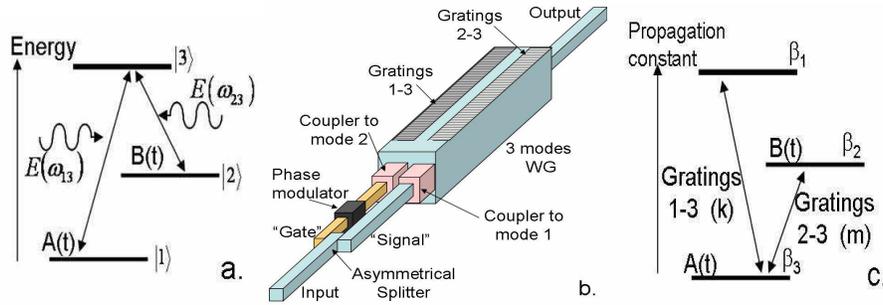


Fig. 1. (a). Coherent EIT configuration (b) Schematics of an equivalent spatial switching device (c) The propagation constants diagram in the interaction region. m and k are the corresponding coupling coefficients.

The analysis of modal propagation in the interaction regime, for "weak" gratings, can be performed by the coupled mode theory [11] and it is completely equivalent to the well known perturbation analysis of the atomic EIT. We employ the conventional set of equations for the forward propagating modes for resonant coupling conditions. The "weak" gratings assertion assists us in selecting only the resonantly coupled modes (rather all modes including radiation), and enabling the integration of the amplitude over a gratings period due to the small change:

$$\partial_z A = jkC \quad \partial_z B = jmC \quad \partial_z C = jkA + jmB \quad (1)$$

where A, B and C are the respective complex amplitudes (integrated over a gratings period) of mode #1 (signal), #2 (gate) and #3 (drain) modes; k and m are the coupling coefficients as depicted in Fig. 1(c). We solve this equation with an input signal in mode #1 and zero initial power at the drain mode #3:

$$A(0) = 1 \quad C(0) = 0 \quad (2)$$

The initial amplitude of the gate mode (#2): B(0) will determine the output of the device (on or off).

The solution of Eq. (1) is:

$$A(z) = 1 + jC_0 \frac{k}{n} (1 - \cos(nz)) \quad B(z) = -\frac{k}{m} - jC_0 \left(\frac{k^2}{mn} + \frac{m}{n} \cos(nz) \right) \quad C(z) = C_0 \sin(nz) \quad (3)$$

where $n^2 = (k^2 + m^2)$ and C_0 is a constant depending on the initial excitation of the gate mode, which determines the switch state. We define the states as:

"On" state:

$$kA(z=0) + mB(z=0) = 0 \quad (4a)$$

$$C_0 = 0 \quad (4b)$$

$$A(z) = 1 \quad B(z) = -\frac{k}{m} \quad C(z) = 0 \quad (4c)$$

Under these initial conditions a steady-state solution is obtained, where the input signal propagates through the device with virtually constant amplitude – equivalent to the so called "dark" state of the atomic system. The required ratio between the signal and gate amplitudes is determined by the ratios of the coupling coefficients.

"Off" state

$$kA(z=0) - mB(z=0) = 0 \quad (5a)$$

$$C_0 = 2j \frac{k}{n} \quad (5b)$$

$$A(z) = 1 - 2 \frac{k^2}{n^2} (1 - \cos(nz)) \quad B(z) = -\frac{k}{m} + 2 \frac{k}{n} \left(\frac{k^2}{mn} + \frac{m}{n} \cos(nz) \right) \quad C(z) = 2j \frac{k}{n} \sin(nz) \quad (5c)$$

Here, by flipping the initial relative signal - gate phase, the input signal can be completely blocked (periodically), which is equivalent to the "bright" state of the atomic. The maximum signal to gate amplitude ratio for completely blocking the signal is 3 as obtained by:

$$A(L_{device}) = 0 \quad \Rightarrow \quad 1 \geq \cos(nL_{device}) = \frac{k^2 - m^2}{2k^2} \geq -1 \quad (6a)$$

$$B(L_{device}) = \frac{k^2 - m^2}{km}, \quad C(L_{device}) = j \frac{k^2 - m^2}{kn} \quad (6b)$$

To validate the results, a slab waveguide device was simulated, using full vectorial beam propagation method (FVBPM) [12]. The interaction zone is comprised of Silicon-Nitride slab $n_{core}=2$ surrounded by glass plates with $n_{clad}=1.44$; the core width is $1.6\mu\text{m}$ and it supports 3 guided modes at $\lambda_0=1.55\mu\text{m}$. Two spatial sinusoidal gratings with refractive index modulation ($\sim 2.5\%$ depth) – with periods matching the intermodal propagation constant difference were imposed on the waveguide core [Fig. 2(a)]. The simulation results are depicted in Figs. 2(b)-2(c). Although slight oscillations of the amplitude are observed in the "on state" (absent in the equation due to the slowly varying amplitude assumption), the signal is almost completely transferred to the output port in the "on state", while almost completely eliminated in the "off" one, for signal/gate input power ratio of ~ 3 (for MZI this power ratio is 1). The extinction ratio of this non optimized switch is 16dB, which is accepted for practical modulators. The imperfect light stopping of the "off" state is due to the oscillations and background scattering by the gratings.

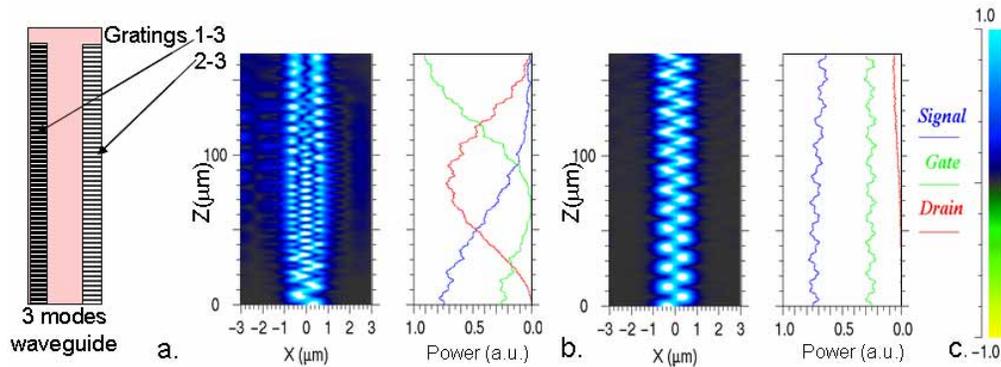


Fig. 2. Simulation results (a) Schematic top view of the simulated device; The total electric field amplitude and the power at the three modes are depicted for (b) "off" – no output signal.; (c) "on" - signal out

3. Back reflection switch with double-period slab dielectric waveguide

An important variant of the above inverse lambda scheme is when one of the modes is selected to be a backward propagating mode (Fig. 3). In this figure we represent by solid lines the propagation constants of the "signal" "gate" and "drain" modes which are the first and second forward propagating modes and third backward mode respectively. These modes are participating in our switching scheme, while the complimentary modes (dashed line in Fig. 3), are propagating in the opposite direction and do not interact with the participating modes even when we apply the proper k and m couplings, as outlined in Fig. 3. This scheme does not have a quantum atomic analog due to the fact that back propagation is equivalent to time reversal which is forbidden.

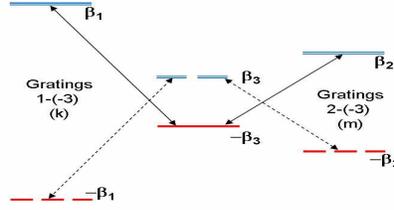


Fig. 3. Level diagram of the back reflection switch (non participating modes – dashed lines)

In this scheme the periodicity does not exist, allowing for a definite and robust switching device without requiring length precision. The signal is reflected, while the gate is in the "off" state and transmitted while the gate is "on".

The set of coupled mode equations are:

$$\partial_z A = jkC \quad \partial_z B = jmC \quad \partial_z C = -jA - jB \quad (7)$$

where A, B and C are the respective complex amplitudes (integrated over a gratings period) of first and second forward and third backward modes. We solve this equation for the following initial conditions:

$$A(0) = 1 \quad C(L) = 0 \quad (8)$$

where L is the device length. The initial phase of the gate mode will be determined according to the requested state of the device. The general solution of set Eq. (7) is:

$$A(z) = 1 + jC_0 \frac{k}{n} (\cosh(n(z-L)) - \cosh(nL)) \quad (9a)$$

$$B(z) = -\frac{k}{m} + j \frac{C_0}{n} \left(m \cosh(n(z-L)) + \frac{k^2}{m} \cosh(nL) \right) \quad (9b)$$

$$C(z) = C_0 \sinh(n(z-L)) \quad (9c)$$

where $n^2 = (k^2 + m^2)$ and C_0 is a constant determined by the initial conditions.

The "On" state:

$$kA(z=0) + mB(z=0) = 0; C_0 = 0 \quad (10a)$$

$$A(z) = 1 \quad B(z) = -\frac{k}{m} \quad C(z) = 0 \quad (10b)$$

exhibits perfect transmission of the input signal to the output port.

Flipping the phase of the gate generates the "Off" state:

$$kA(z=0) - mB(z=0) = 0; C_0 = -2j \frac{k}{n} \frac{1}{\cosh(nL)} \quad (11a)$$

$$A(z) = 1 + 2 \frac{k^2}{n^2} \frac{(\cosh(n(z-L)) - \cosh(nL))}{\cosh(nL)} \quad (11b)$$

$$B(z) = \frac{k(k^2 - m^2)}{mn^2} + 2 \frac{km}{n^2} \frac{\cosh(n(z-L))}{\cosh(nL)} \quad (11c)$$

$$C(z) = -2j \frac{k}{n} \frac{\sinh(n(z-L))}{\cosh(nL)} \quad (11d)$$

For a vanishing transmission, the required signal to gate amplitude ratio is bounded by 1:

$$A(z=L) = 0 \Rightarrow \frac{m^2 - k^2}{n^2} = 0 \Rightarrow k = m \quad (12a)$$

The simulated performance of an actual reflection switch structure (similar to that described in the previous section, except for the gratings periods) is summarized in Fig. 4 and is exhibiting an extinction ratio of ~16dB, for a signal to gate ratio of ~1.

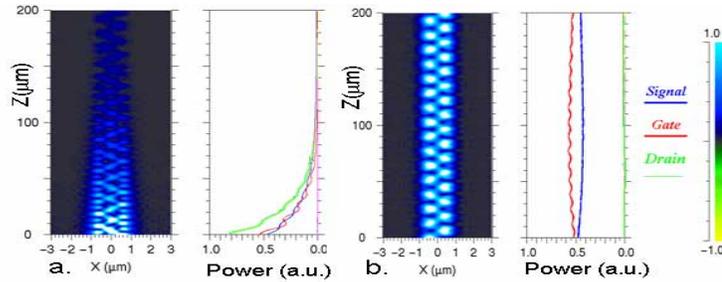


Fig. 4. (a). "off" – all signal reflected. (b) "on"- signal transmitted

4. Switch based on "unmotivated" coupling

In both previous cases we applied "force" (gratings) to initiate power scattering between modes. Here we use a different concept for the interaction region, which is based on three evanescently coupled waveguides as depicted in Fig. 5(a), but yet the same embedded mechanism holds. The evolution (propagation) of well prepared mode combinations is preserving the principles of EIT without the necessity to apply an additional force to the system. This stems from the similarity between the coupling effect due to external electromagnetic fields (gratings in the spatial case) and tunneling (directional coupling in the spatial case) [5]. The scheme here is the same as of case 1 except that the signal and gate are launched as inputs of waveguide 1 and 2 respectively, while an auxiliary waveguide serves for the realization of the drain (state 3). The coupled mode theory of case 1 is applied to a modal basis set of the separated waveguides, which differs only in the detailed definition of the coupling constants [1].

We simulated by FVBPM the propagation in the interaction zone, comprised of three identical slab dielectric waveguides with $d_{\text{core}}=0.5\mu\text{m}$ and $n_{\text{core}}=2$ surrounded by a substrate $n_{\text{clad}}=1.44$. The waveguides spacing are $d_1=0.5\mu\text{m}$ and $d_2=0.375\mu\text{m}$. The required Signal to Gate power ratio of this device is 3 independently on the absolute signal power. The performance of the switch is shown in Figs. 5(b)-5(c). The extinction ratio of this actual switch according to the simulation is $\sim 16\text{dB}$.

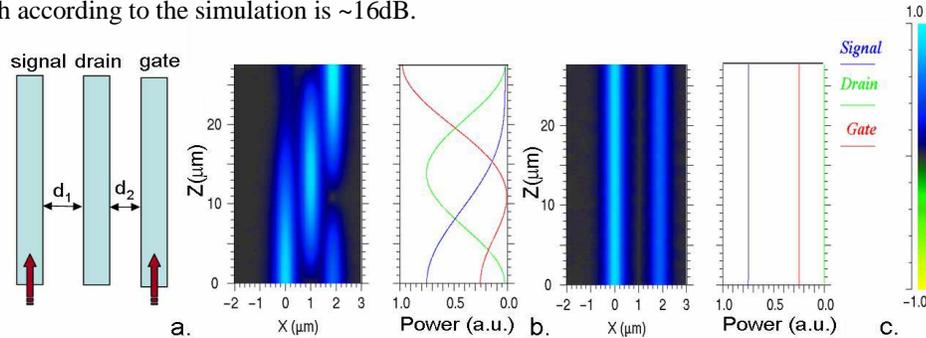


Fig. 5. Simulation results (a) Schematics top view of the simulated device; the total electric field amplitude and the power at the three waveguides are depicted for (b) "off" – no output signal; (c) "on" - signal out

It is worthwhile to note that this configuration is the one which is similar to an MZI based switch – the output combiner of the latter is based on two waveguides directional coupler, and yet it provides a generalization and broadening of the MZI concept – providing a new dimension of design flexibility.

5. Conclusions

We presented optical waveguide devices inspired by the atomic EIT configuration, and showed that transitions between modes can be controlled linearly, similarly to atomic transitions, enabling a broad family of photonic switching configurations.