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Beam splitter and combiner based on Bloch oscillation in a spatially modulated waveguide array

Yiqi Zhang[1], Milivoj R Belić[2], Weiping Zhong[3], Feng Wen[1], Yang Guo[1], Yao Guo[1], Keqing Lu[4] and Yanpeng Zhang[1]

[1] Key Laboratory for Physical Electronics and Devices of the Ministry of Education & Shaanxi Key Lab of Information Photonic Technique, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China
[2] Science Program, Texas A&M University at Qatar, PO Box 23874 Doha, Qatar
[3] Department of Electronic and Information Engineering, Shunde Polytechnic, Shunde 528300, People's Republic of China
[4] School of Electronics and Information Engineering, Tianjin Polytechnic University, Tianjin 300387, People's Republic of China

E-mail: zhangyiqi@mail.xjtu.edu.cn, milivoj.belic@qatar.tamu.edu and ypzhang@mail.xjtu.edu.cn

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Abstract

We theoretically and numerically investigate light beam propagation in a periodic waveguide array that is spatially modulated with a certain structure which brings novel functionalities to the array. We find that a light beam may split, coalesce, deflect, and be localized during propagation in a simply modulated waveguide array. The phenomena described originate from the Bloch oscillation and supply a convenient method for fabricating on-chip beam splitters and beam combiners.

Keywords: waveguide arrays, Bloch oscillation, beam splitter, beam combiner

(Some figures may appear in colour only in the online journal)

1. Introduction

It is well known that a light beam undergoes discrete diffraction when propagating in waveguide arrays or modulated photonic crystals [1–10]. Such diffraction is the result of so-called evanescent coupling among adjacent waveguides [11]. In the coupled mode regime, the ballistic propagation of light in a one-dimensional periodic system can be described by the following simple dimensionless discrete model:

$$i\frac{\partial \psi_m}{\partial z} + C\left(\psi_{m-1} + \psi_{m+1}\right) = 0 \qquad (1)$$

where m is an integer and ψ_m is the modal amplitude in the mth waveguide. Here C is the coupling coefficient, which can be assumed to be $C = 1$. The analytical solution to this coupled-mode equation can be written as $\psi_m(z) = J_{-m}(2z)\exp(-im\,\pi/2)$ for a specific case when only the $m = 0$ waveguide is excited. It should be noted that equation (1) is just a crude approximation of continuous media, but it works well for an array of narrow waveguides. It continues to work well even when nonlinearity is introduced, as exemplified in a number of experimental accounts. In this case diffraction may be balanced by nonlinearity so that localized trapped beams (discrete solitons) can appear [12–19].

To localize a beam in bulk or atomic media, nonlinearity is generally required [20–23]. However, to localize a beam in a discrete system, nonlinearity is not a must. Through manipulation of waveguide arrays, a light beam may exhibit *Bloch oscillation* during propagation, which prohibits the appearance of discrete diffraction and may localize the beam linearly [24–29]. The basic dimensionless model for investigating optical Bloch oscillation can be written as [24]

$$i\frac{\partial\psi_m}{\partial z} + \alpha m\psi_m + C\left(\psi_{m-1} + \psi_{m+1}\right) = 0, \quad (2)$$

in which a linear term appears that comes from the modulation of the refractive index, and α is a coefficient used to weigh the refractive index change. The corresponding analytical solution for single waveguide excitation when $C = 1$ is now $\psi_m(z) = J_{-m}[4\sin(\alpha z/2)/\alpha]\exp[im(\alpha z - \pi)/2]$ [24]. Hence, by designing and fabricating the periodic waveguide arrays inventively, interesting optical phenomena may be observed [30–33]. It is worth mentioning that phenomena associated with optical periodic systems can be used to emulate quantum events, owing to the equivalence of the paraxial wave equation and the quantum-mechanical Schrödinger equation [11, 34–38].

In this paper, enlightened by the Bloch oscillation that occurs in periodic waveguide arrays, we design such arrays purposefully to manage light behavior during propagation (e.g., fission, coalescence, deflection, and localization of beams) and use it to produce useful optical devices. Waveguide arrays with certain features as studied in this paper may find potential applications in the production of on-chip optical devices, such as beam splitters and beam combiners.

This paper is organized as follows. In section 2, we introduce the model and discuss a special case where only waveguides with $m \leqslant 0$ are modulated. In section 3 we broaden the analysis to beam splitters based on the modulation of both positive and negative waveguides. Section 4 deals with beam combiners, and section 5 concludes the paper.

2. Waveguide array with $m \leqslant 0$ members modulated

To enable a more general design of waveguides, we rewrite the parameter α as α_m, which may depend on m. Here, for convenience, we denote the waveguides with $m > 0$ as positive waveguides, those with $m < 0$ as negative waveguides, and the one with $m = 0$ as the zero waveguide, respectively. Equation (2) is rewritten as

$$i\frac{\partial\psi_m}{\partial z} + \alpha_m m\psi_m + C\left(\psi_{m-1} + \psi_{m+1}\right) = 0. \quad (3)$$

Actually, the coupled mode equations (equations (1) and (2)) should be written in different forms for different regions, e.g., when there is an interface between waveguide arrays or at the edges of an array. However, we assume that the coupling constant between adjacent waveguides is always the same and that there is no difference in the propagation constants of isolated waveguides between different regions in an array. Therefore, the coupled mode equation remains the same, even though there might be interfaces in the waveguide array. We should note that wave localization at interfaces (surface waves [39, 40], Tamm states [41]) and the dynamics of waves (trapping [42], reflection [43, 44]) related to waveguides have been subjects of intense research effort in the last few years [45, 46].

In this section, we let $\alpha_m = 0$ if $m > 0$ and let α_m be constant if $m \leqslant 0$, for example,

$$\alpha_m = \begin{cases} 0.5 & m \leqslant 0, \\ 0, & m > 0. \end{cases} \quad (4)$$

We can now see Bloch oscillation in the region $m < 0$ and discrete diffraction in the $m > 0$ region if $|m|$ is large enough. Since the Bloch oscillation spreads over $\sim 8/\alpha_m = 16$ waveguides in this case [24], if the waveguides are excited by an incident beam peak at $m \leqslant -12$, a complete Bloch oscillation is exhibited. In addition, the beam energy strongly couples into the positive waveguides as the incident beam gets closer to the zero waveguide.

In figures 1(a)–(h), we show the propagation of an incident beam of Gaussian profile when the waveguide is excited by the beam peak at waveguides −10, −8, −6, −4, −2, 0, 2, and 4, respectively. Note that the color scale is arbitrary (also true throughout this paper) because the system is linear. The width of the input beam is chosen such that the effects of interest are clearly visible. Later more discussion on the choice of width is provided. In figure 1(a), the beam energy coupled into the positive waveguides is tiny, so the Bloch oscillation is nearly unaffected. When the waveguide excited by the beam peak is −8, as shown in figure 1(b), the beam energy coupled into the positive waveguides increases and exhibits Zener-like tunneling [29, 47], which is due to the discrete diffraction of the part of the oscillating beam that has coupled into the positive waveguides. When the excited waveguide is closer to the zero waveguide, as displayed in figures 1(c)–(e), more of the energy (figure 1(c)) and even all the energy (figures 1(d) and (e)) may couple into the positive waveguides. In figure 1(d) in particular, the beam seems also to be localized to some extent. The reason for this phenomenon is that the oscillating beam initially turns upward and at the same time the energy is coupled into the positive waveguides; thus the diffraction is equivalent to that of an obliquely incident beam [3].

If the waveguide excited by the beam peak is precisely the zero waveguide, as shown in figure 1(f), the incident beam energy is distributed in the positive and negative waveguides equally and undergoes discrete diffraction and Bloch oscillation, respectively. On the one hand, the discrete diffraction is reflected into the positive waveguides; on the other hand the Bloch oscillation also strongly couples energy from the negative waveguides with the positive waveguides. As a result, the beam exhibits mainly discrete diffraction into the positive waveguides.

When the waveguide excited by the beam peak is positive, most of the beam energy undergoes discrete diffraction. And the diffraction is totally reflected internally into the positive waveguides when the peak approaches the zero waveguide, as displayed in figures 1(g) and (h). Note the Goos–Hänchen shift [46], visible in the negative waveguides.

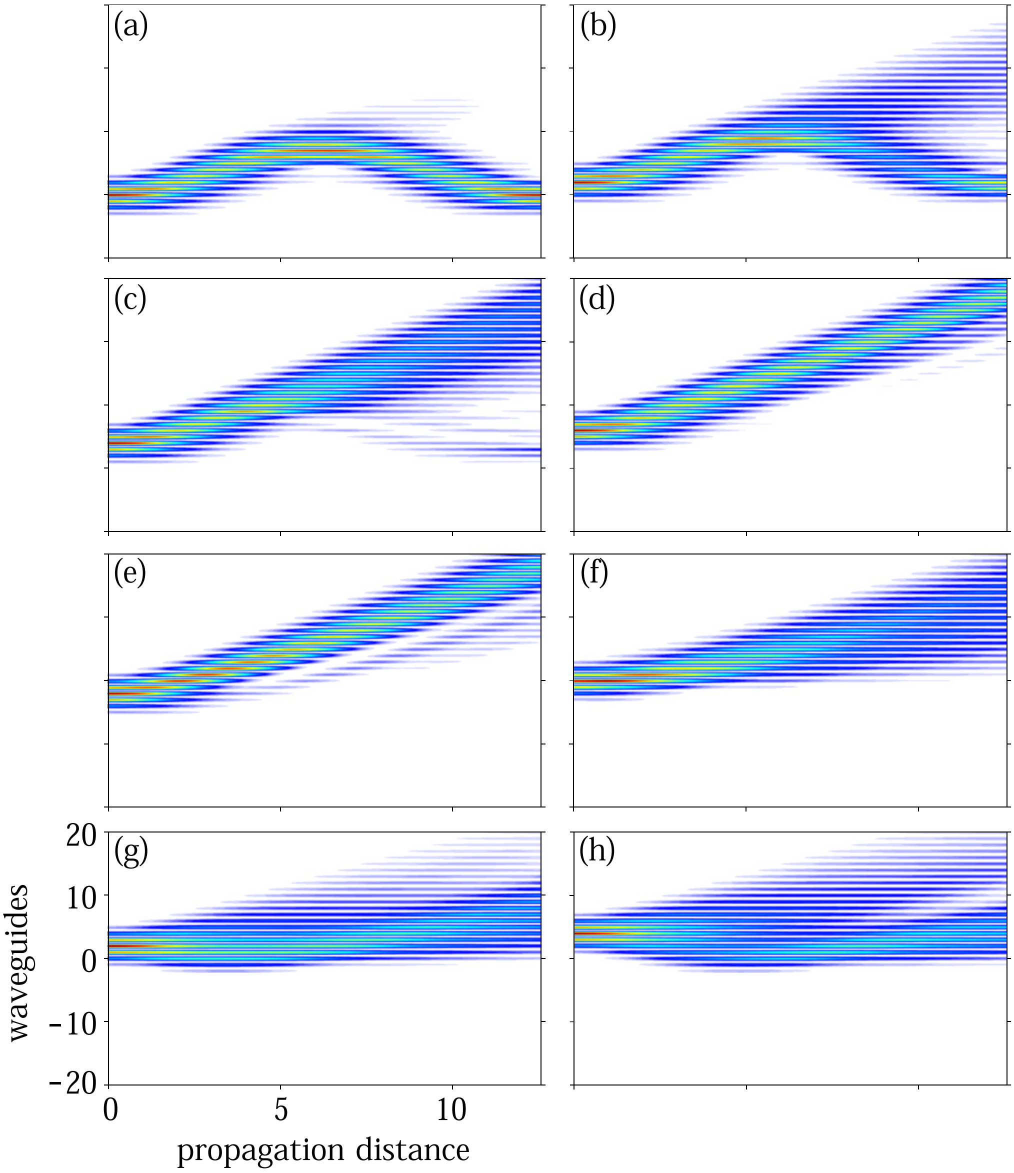

Figure 1. Propagation of a Gaussian light beam in a periodic waveguide array with $\alpha = 0.5$ for $m \leqslant 0$ and $\alpha = 0$ for $m > 0$. (a)–(h) Peaks of the incident beams are located at waveguides −10, −8, −6, −4, −2, 0, 2, and 4, respectively.

3. Beam splitter based on a V-type modulated waveguide array

Instead of only modulating the negative waveguides, we now modulate both the positive and the negative waveguides by defining α_m as

$$\alpha_m = \begin{cases} -0.5 & m \leqslant 0, \\ 0.5 & m > 0. \end{cases} \quad (5)$$

The modulated waveguides exhibit a V-type intersection, which means the bigger the value of $|m|$, the higher the index ramp. Thus, if two beams are launched symmetrically into the negative and positive waveguides, they first repel and then attract each other, to oscillate along parallel directions. In other words, the beams deflect away from the zero waveguide within the propagation distance $z < \pi/|\alpha_m|$ and then move closer to the zero waveguide within the distance $\pi/|\alpha_m| \leqslant z < 2\pi/|\alpha_m|$. They do not affect each other much if they do not overlap at the initial positions (i.e., they do not reach across the zero waveguide). On the other hand, if a wide incident beam extends across the zero waveguide, it will be divided. From this standpoint, the foregoing arrangement may be used to make a beam splitter [48].

In figure 2, we depict the propagation of a Gaussian beam in a V-type modulated waveguide array within the half-period of the Bloch oscillation. The zero waveguide is excited by the beam peak, and the width of the Gaussian covers approximately the ±4 waveguides; hence, the beam is equally divided into the positive and negative waveguides during propagation. The beam readily splits into positive and negative parts of equal energy and transverse spread. In addition, as shown by the input and output beam intensities in the right panel in figure 2, the maximum intensities of the output beam are located at the ±8 waveguides, and the divided beams exhibit

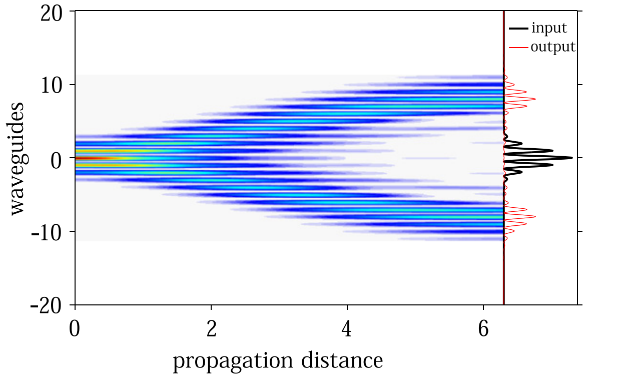

Figure 2. A Gaussian beam splits during propagation in a V-type modulated waveguide array. The zero waveguide is excited by the beam peak. The curves in the right panel are the corresponding beam intensities at the input and output places, respectively.

the same structure as the initial beam. In a word, both the efficiency and the resolution of the fission are high, which means that such fission can be used to produce high-quality beam splitters. We emphasize that this kind of beam splitter is based on Bloch oscillation only, which is different from the situation reported previously [48]. We believe that this beam splitter is easy to implement and can be conveniently tuned (e.g., the fission width and the fission length) through the parameter α_m.

4. Beam combiner based on a Λ-type modulated waveguide array

It is interesting to ask what will happen if the modulation is of the Λ-type, that is, an inverted case of the V-type. For this case, α_m can be written as

$$\alpha_m = \begin{cases} 0.5 & m \leqslant 0, \\ -0.5 & m > 0. \end{cases} \quad (6)$$

Similar to the case of a V-type modulated waveguide array, the incident beam exhibits Bloch oscillation if the excited waveguide number $|m|$ is not smaller than $\sim 6/|\alpha_m|$.

We first investigate the propagation of a Gaussian beam with the peak exciting the zero waveguide, as displayed in figure 3(a). One can see that the beam energy is first attracted to the zero waveguide and then repelled into the positive and negative waveguides, and this process proceeds periodically, which is quite similar to the Fermi–Pasta–Ulam (FPU) recurrence discovered in fibers [49, 50]. The reason for the recurrence phenomenon is obvious—in essence, it is Bloch oscillation that results from the combined effects of discrete diffraction and total internal Bragg reflection [24]. It should be mentioned that FPU recurrence is a nonlinear effect, whereas recurrence by Bloch oscillation is a linear effect. It is also worth mentioning again that Bloch oscillation causes a linear localization: the beam spreads over waveguide arrays no more than the incident beam does if more than one waveguide is excited by the beam and the zero waveguide is excited by the peak. The effect is independent of the

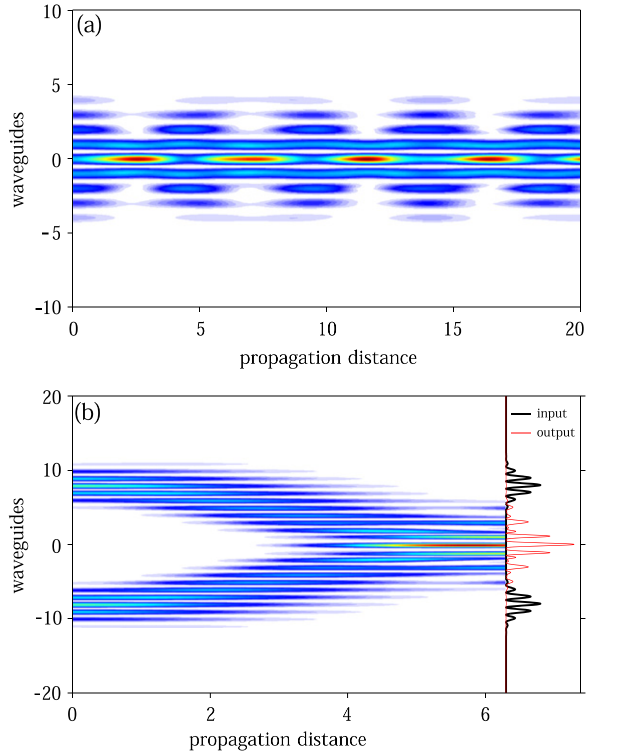

Figure 3. (a) Propagation of a Gaussian beam in a Λ-type modulated waveguide array with the zero waveguide excited by the beam peak. A Fermi–Pasta–Ulam recurrence-like oscillation happens during propagation. (b) Two Gaussian beams launched from positive and negative waveguide sides coalesce during propagation. The curves in the right panel depict the corresponding beam intensities at the input and output places, respectively.

parameter α_m. Thus, Bloch oscillation in waveguide arrays is capable of capturing some nonlinear optical effects in bulk, such as beam recurrence and localization.

When two beams are launched into the positive and negative waveguides, they first attract each other and start to oscillate, which is different from the V-type case. If the excited waveguide number $|m| \leqslant 6/|\alpha_m| = 12$, they coalesce during propagation. This kind of coalescence is shown in figure 3(b). The two Gaussian beams, which excite the ± 8 waveguides respectively, oscillate about the zero waveguide. Since $|m| < 12$, both beams can reach the zero waveguide, which causes coalescence of the two beams. Similar to figure 2, figure 3(b) displays the input and output intensities. The coalesced beam is nearly Gaussian except for the intensities distributed in the ± 2 waveguides; they are attenuated due to destructive interference between the oscillating beam and its reflection. From figure 3(b), one can see that this kind of coalescence can be used to produce a beam combiner, which also results from only the Bloch oscillation in the waveguide array. Similar to the beam splitter shown in figure 2, such a beam combiner possesses high working efficiency and resolution, and it can be conveniently tuned.

Finally, we point to the role the incident Gaussian beam width plays in the beam splitting/coalescence. The beam width determines how many waveguides are effectively excited. If the beam width is small and only one waveguide is effectively excited, the resultant fission and coalescence will exhibit low efficiency because the Bloch oscillation produces a beam behaving like a breather, which is difficult to split or coalesce. On the other hand, if the beam width is large, the fission and coalescence will also exhibit low efficiency because the beam will spread over many waveguides, which will produce a complex interference pattern. The resultant beam will display a complex structure that may not reproduce the input beam well. Thus, an optimum is reached if a moderate beam width is chosen, as in figures 2 and 3. This optimum corresponds to the estimate applied in the figures, wherein up to $8/\alpha$ waveguides may be effectively covered for a fixed coupling factor α; this choice makes the split/coalesced beams close to the initial beams.

5. Conclusion

In conclusion, we have investigated the propagation of beams in linearly modulated waveguide arrays. By elaborately designing the form of modulation, the beams can split, coalesce, deflect, and be linearly localized during propagation. These phenomena can be understood by using only the concept of Bloch oscillation. We also find that the devices suggested can be conveniently tuned through a single parameter, α_m. Although we explored only the simplest choices for α_m, more elaborate modulations will lead to more diverse propagation effects. On the basis of beam fission and coalescence, we believe that prototypes of all-optical devices, such as beam splitters and beam combiners, can be simply produced in waveguide arrays with high work efficiency and resolution.

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