Confining light flow in weakly coupled waveguide arrays by structuring the coupling constant: towards discrete diffractive optics

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Abstract: Structuring the coupling constant in coupled waveguide arrays opens up a new route towards molding and controlling the flow of light in discrete structures. We show coupled mode theory is a reliable yet very simple and practical tool to design and explore new structures of patterned coupling constant. We validate our simulation and technological choices by successful fabrication of appropriate III-V semiconductor patterned waveguide arrays. We demonstrate confinement of light in designated areas of one-dimensional semi-conductor waveguide arrays.

OCIS codes: (130.2790) Guided waves; (130.3120) Integrated optics devices; (230.3990) Micro-optical devices; (080.1238) Array waveguide devices; (350.3950) Micro-optics

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#103693 - $15.00 USD Received 4 Nov 2008; revised 30 Dec 2008; accepted 4 Jan 2009; published 17 Feb 2009

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#103693 - $15.00 USD Received 4 Nov 2008; revised 30 Dec 2008; accepted 4 Jan 2009; published 17 Feb 2009

1. Introduction

Light propagation in homogeneous arrays of weakly coupled waveguides, i.e. identical waveguides identically coupled, has been studied extensively [1,2, and references therein]. In homogeneous arrays, light injected in a single guide or several waveguides couples to more and more waveguides as it propagates along the longitudinal direction Z. The widening distribution of lit waveguides thus exhibits a behavior analogous to diffraction [3]. Propagation of Floquet-Bloch waves in this periodic discrete 1D or 2D guided environment displays several interesting features. Characteristic discrete diffraction can be observed, and the light distribution within the array has a beam-like behavior and follows a specific diffraction relation [4]. In these weakly coupled waveguide arrays, the key parameters governing light propagation from one waveguide to the next and throughout the whole array are the coupling constant C between neighboring waveguides and the propagation constant β of individual waveguides.

From a fundamental point of view, these archetypal discrete systems enable exploration of universal discrete-like dynamics [5] and discrete non-linear behavior [6] via the study of the field evolution in each individual waveguide. They have been exploited both in the linear [7,8] and non linear [2,9,10] regimes to demonstrate Bloch oscillations [7,8], discrete diffraction engineering [11] and discrete optical solitons [4,12,13]. Beside the intrinsic fundamental interest of these elegant studies started in the 90s, all-optical signal processing in the efficient, sturdy and compact domain of guided optics has been pursued for several decades in couples of waveguides [e.g. 14,15] and waveguide arrays [e.g. 16-18]. For example, several schemes - phase [19] or power [20-23] controlled - have been proposed to steer a propagating discrete soliton in order to achieve multiport switching.

In practice though, experimental demonstrations of advances towards signal processing [10,24-26] remain scarce. One reason could be that the studied arrays constitute indeed for the Floquet-Bloch waves a homogeneous meta-material analogous to a bulk material in optics, acoustics or electronics, which is limiting in all domains when signal processing is at stake. Attempts of signal processing in homogeneous arrays, i.e. guiding, steering, routing, switching etc. of beams, thus relied on non-linear effects and self localization, which are fruitful routes but demand high optical power [21], as well as subtly modified structures [27] and intricate schemes, all the more so as the natural mode which carries information in a non linear homogeneous lattice is the discrete soliton, a challenging object of exploration [28] in itself.

Extending the free space approach of homogeneous arrays, the inspiring theoretical work of Syms [29], carried out in the context of supermode control in transverse-modelocked lasers, hinted that reflection, refraction and guiding of beam-like light distribution within the array could be obtained also by building boundaries between semi-infinite homogeneous arrays of different characteristics. This seminal functionalization of the discrete guided array space has remained implicit up to now to our knowledge, except for a recent experimental demonstration of refraction [30]. Other works involving array inhomogeneity [8,22,25,31-38] followed a different path, well-grounded in the optics/nonlinear optics framework. They rely on the creation of defects and corrections to or gradients of the propagation constant β to mimic dc or ac electric force [8], create defects propitious for strongly localized states [39] or switch prototypes [32], and stabilize [26,40] or manipulate [41] solitons.

In search of alternative routes for light control in waveguide arrays, we propose here to explore and implement explicitly another instance [42] of *discrete refractive optics* by:

- fragmenting the infinite periodic discrete space of the homogeneous array into a structured array, i.e. a combination of finite or semi-infinite arrays where the key parameter governing the inter-guide coupling – *the coupling constant C, and not β as in previous works* – is different, thus building what we will call "*C-patterns*".

- introducing light processing functions in a built-in functionalized space, i.e. manipulation of Floquet-Bloch waves across interfaces between zones with different coupling constants.

#103693 - $15.00 USD Received 4 Nov 2008; revised 30 Dec 2008; accepted 4 Jan 2009; published 17 Feb 2009

In this paper, we present a first experimental demonstration of this concept, i.e. a demonstration that functional C-patterned arrays can indeed be designed, modeled, realized, and operated. Our test patterns are light-confining C-patterns which we call *channels*. In section 2, we validate a simple coupled-mode (tight-binding) model and discuss the modes that can be expected in channels. In section 3, we describe the sample, a first realization of a C-pattern, before demonstrating experimentally light confinement in designated areas in section 4. This finally shows that such C-patterns can be excellent realizations of discrete refractive optics schemes and designs.

2. Modes of C-pattern channels and validity of the coupled-mode-theory approach

Similar to [29], we propose creating a characteristic guided mode (i.e. light confinement within a specific zone of the structured array) in a composite waveguide array. Light confinement is achieved in a N-guide homogeneous array of type 1 (the channel), sandwiched between two semi-infinite confinement barriers made of homogeneous arrays of type 2. Homogeneous arrays of type 1 or 2 are identical except for their characteristic C: type 1 has a coupling constant C_1 and type 2 has a coupling constant $C_2 < C_1$.

We will base our assessment of channel structures, with respect to both the modal structure and the actual propagation, on the widely-used coupled-mode theory (CMT) approximation which can be derived from Maxwell equations in the slowly varying envelope approximation. This approximation is generally taken as valid when the coupling is weak enough ($C \ll \beta$). We propose here to test its relevance in a more refined manner for the case of channels, by checking that their propagation coefficients and eigenmodes shapes are correctly described by CMT; although the methods we use are already known separately, such a test has not been reported yet to our knowledge. Channel modes can be computed as direct numerical solutions of Maxwell equations, for instance via a finite element method (FEM) analysis. They can also be derived simply within CMT in the following way. The reduced CMT propagation equation along the waveguide axis Z is $\partial a_m/\partial z = i\left(c_{m,m+1}a_{m+1} + c_{m,m-1}a_{m-1}\right)$ [11], where z is the reduced propagation coordinate $=C_1 Z$, $c_{i,,j}$ are reduced coupling constants $C_{i,j}/C_1$, and a_m is the amplitude of the individual-waveguide mode carried by the m-th waveguide (~ electric field amplitude at its center). Solutions sought as Floquet-Bloch plane waves $a_m(z) = b_m \exp(ik_z z)$ or eigenmodes can be computed by a method derived from the one used in laser arrays [43]: for any C-pattern, mode shapes and wavevectors are respectively the eigenvectors $b^{(p)}$ and eigenvalues $k_z^{CMT\ (p)}$ (p=1,…,N) of the adjacency matrix, whose only non-zero elements are two diagonals of the reduced coupling constants. The relationship of the reduced wavevectors k_z in CMT with the actual propagation constants β is given by

$$k_z = \frac{\beta - \beta_0}{C_1} \tag{1}$$

where β_0 is the propagation coefficient of the isolated waveguide. Hence reduction of the propagation constants β to $(\beta-\beta_0)/C_1$ wavevectors allows comparing them to k_z^{CMT} predictions.

We test that CMT does describe correctly the channel modes in the extreme case of a perfectly confined channel (C_2=0, i.e. no waveguides around those in the channel), for which CMT solutions are analytical and FEM calculations do not require too large structures. The FEM calculations – Comsol software package – are conducted on the actual experimental InGaAsP shallow-ridge layered structure described in the next section. The ladders of wavevectors and some corresponding mode shapes obtained in various perfectly confined channels are compared in Fig. 1. As expected, channels are naturally multimode structures with as many modes as waveguides.

#103693 - $15.00 USD Received 4 Nov 2008; revised 30 Dec 2008; accepted 4 Jan 2009; published 17 Feb 2009

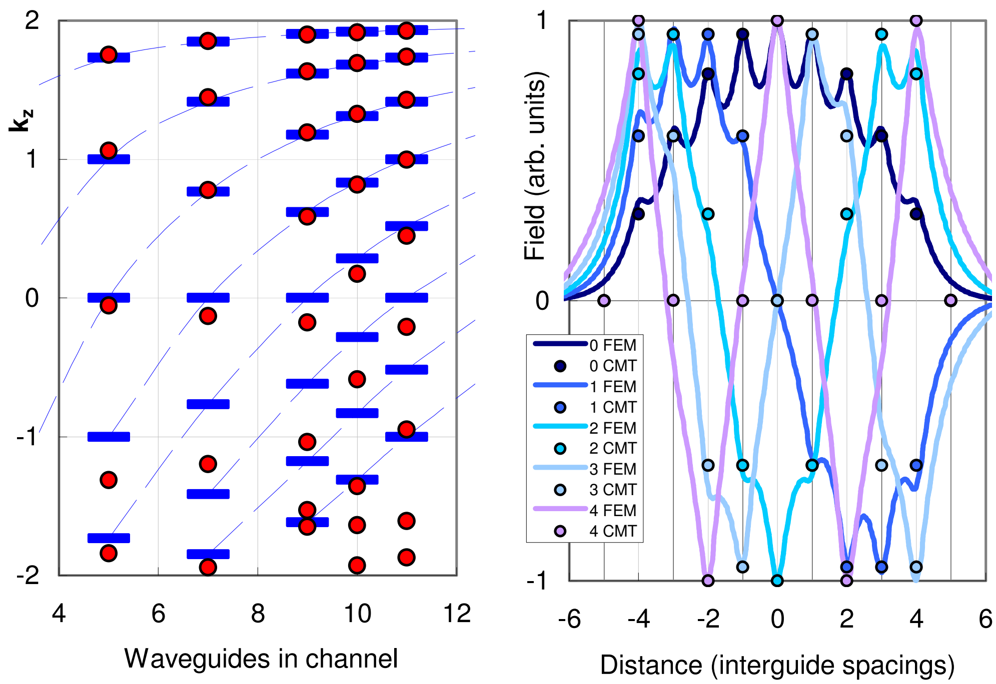

Fig. 1. Modes of perfectly confined channels. Left: Comparison of the dimensionless k_z given by the analytical coupled mode theory (CMT) (k_z^{CMT}, blue bars with dotted lines joining modes of the same order as guide to the eye) and the adjusted finite element method (FEM) numerical solutions ($[\beta^{FEM} - \beta_0]/C_1$, red dots) as a function of the number of guides N in the channel (the C-pattern of type 1); the adjustment is done via Eq. (1) using a single set of parameters (C_1=1.51 mm^{-1}, β_0=13.095µm^{-1}). Right: Comparison of the CMT (dots) and the FEM (lines) normalized amplitude of the electric field along X for the 4 lowest-order modes of a N=9 guide channel; integer abscissas correspond to the centers of the waveguides. In both figures, the layered structure implemented in FEM is the actual experimental epitaxial structure described in section 3, with an inter-guide spacing s similar to the type I zone of the actual sample (s=5 µm).

A very good agreement between FEM and CMT data is obtained, at least for the four or five first modes (highest k_z or β), both on all mode shapes and all wavevector ladders – the various k_z^{CMT} and the various $(\beta^{FEM} - \beta_0)/C_1$ – for a single set of the adjustable parameters (C_1=1.51 ± 0.07 mm^{-1} and β_0=13.095µm^{-1}). The agreement decreases for higher-order modes, due to the fact that FEM data for such modes become increasingly sensitive to boundary conditions; this shows on the increasingly large erroneous tail of the modes outside the channel, and the progressive deviation in wavevector ladders. The comparison between the analytical CMT approximation and the FEM data is indeed an encouraging validation for the very simple CMT approximation that we will use to model the experiments in section 4. It additionally provides us with an accurate determination of the coupling constant of homogeneous arrays required for designing our C-pattern. As checked against our experimental results (not shown) in the case of perfectly confined channels, C values obtained that way are indeed much more reliable than values usually obtained numerically from the beating between the symmetric and antisymmetric modes of two coupled waveguides (same method for channel N=2, k_z=±1).

We therefore use CMT to design channels. By looking at the extension of the evanescent wave across a desired barrier, we estimate a useful and sufficient contrast C_1 / C_2 of 2 for C-pattern interfaces. We also estimate a desired value for the homogeneity of ΔC / C < 10 %.

3. Sample and experimental setup

In practice, we use 1D arrays of shallow-ridge InP-based waveguides operated at a wavelength of 1.55 µm. Following the method described in section 2, we design a layered structure and ridge geometry of appropriate and convenient coupling constant. The structure is carefully designed so that the dependence of C on the various structural parameters (layers thicknesses, ridge width, height and separation) is neither two steep – to ensure homogeneity and reproducibility of the structures – nor too gentle – to conveniently reach the desired ratios C_1/C_2 by tuning one of these parameters. The quality of III-V waveguides enables fabrication of the C-pattern at the chosen working point. The sample thus consists of shallow-ridge waveguides etched 1.5µm deep on top of a stack composed by a 400 nm thick guiding layer of InGaAsP (refractive index 3.337 at 1.55 µm), sandwiched between 1.9 µm thick (upper) and 3.0 µm thick (lower) InP claddings. The ridge width is 1.5 µm. Typical samples are constituted both of homogeneous and structured regions (Fig. 2).

We first validate experimentally the simulation and technological choices in homogeneous systems homogeneous arrays. The source is a conventional 1 mW 1.55 µm cw fiber-output laser. We use a microlensed fiber to inject light at the input face of the sample. The output field is imaged with a x20 or a x8 microscope objective on an infrared camera. To measure the coupling constant of our homogeneous arrays, we compare the CMT simulation of the well-known discrete diffraction output and the experimental output image of the field intensity, when light is injected into the homogeneous arrays via a single waveguide. The samples are 3.4 mm long homogeneous arrays with a constant separation between the centers of the waveguides of s=5 µm (coupling constant C_1) or s=9 µm (chosen so that $C_2=C_1/2$). This propagation length corresponds to about 5 coupling lengths for the C_1 regions. For s=5 µm, we find $C_1=1.55\pm0.08$ mm^{-1}. This value is in remarkable agreement with the value deduced from the left of Fig. 1 in section 2, $C_1=1.51\pm0.07$ mm^{-1}. We also measure $C_2=0.67\pm0.08$ mm^{-1} for s=9 µm. We validate the homogeneity of the sample by checking that the output image from the homogeneous array is not dependent on the guide chosen for the injection. We thus successfully fabricated the simulated homogeneous array of controlled coupling constant. We find the coupling is slightly (± 0.1 mm^{-1}) dependent on the input beam polarization that we henceforward fix to be vertical.

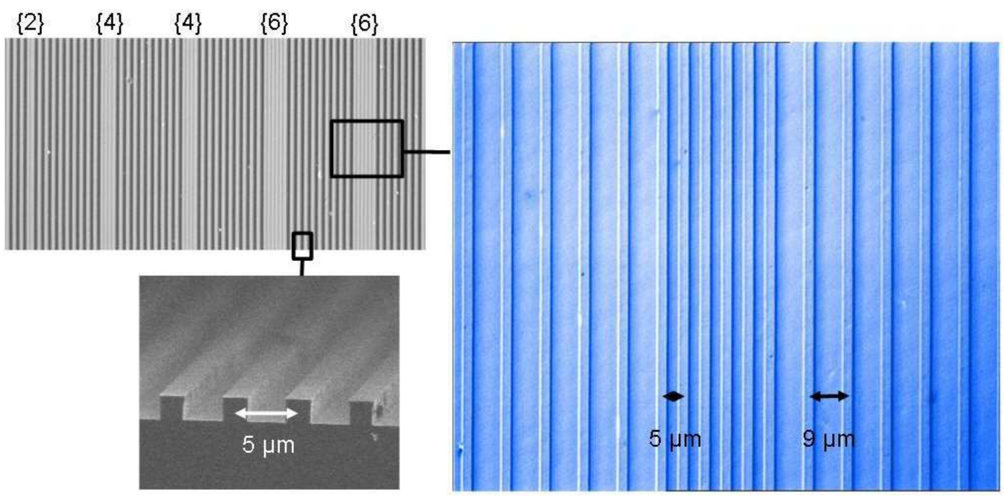

Fig. 2. Views of C-patterned arrays defining channels. Left top: Optical microscopy image of 2, 4 and 6-guide-wide channels. Left bottom: Scanning electron microscope view of the cleaved input face of the sample. Right: Enlargement of the 6-guide-wide channel.

We then study regions where the coupling constant is patterned. They are designed to obtain channels of {N} more strongly coupled waveguides, surrounded by homogeneous semi-

#103693 - $15.00 USD Received 4 Nov 2008; revised 30 Dec 2008; accepted 4 Jan 2009; published 17 Feb 2009

infinite regions of less coupled identical waveguides. For this first experimental demonstration, the coupling is simply structured by varying the spacing between the guides, s=5 µm in the channel (coupling constant C_1) and s= 9 µm for the confining barrier (coupling constant C_2). The C-pattern sample is shown on Fig. 2. A top view of the injection setup is given in Fig. 3.

4. Experimental results

The output images from channels composed of N guides (N=2, 4, 6, 8 and 10) after 3.4 mm propagation are shown in Fig. 3. In contrast with the typical discrete diffraction shown at the bottom of Fig. 3, these experimental data clearly exhibit the desired guiding effect in the more strongly coupled waveguides. The light distribution is indeed localized in the channel which successfully achieves guiding of the wave.

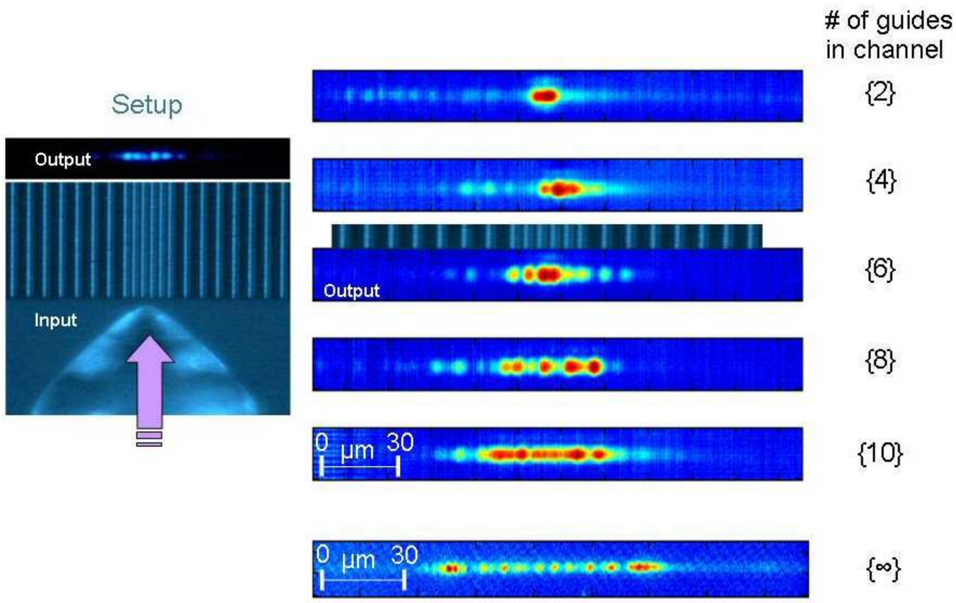

Fig. 3. Left: Top view of the experimental setup: a microlensed fiber injects light into a 6-guide-wide channel. Inside the channel, the ridge separation is s=5 µm. On both barrier sides, the less strongly coupled waveguides are separated by 9 µm. Right: Output intensity maps for various sizes {N} of channels (N more strongly coupled waveguides). Special care has been taken to keep the injection constant (w_0=8.75 µm, see text) for all channels. Bottom: output of a homogeneous array with s=5 µm. Please note that a different microscope objective (MO) and different injection (w_0=5 µm) have been used to image the homogeneous array sample {∞}.

In addition, comparison of the data of Fig. 3 with CMT results is given in Fig. 4. The size of the injection, that is set by the microlensed fiber position and identical for all channel sizes, is chosen experimentally large enough to smooth the discrete propagation patterns, and narrow enough for the light to be injected within the narrower channel. The size of Gaussian injection (waist =8.75 µm) and its position is deduced from the fits.

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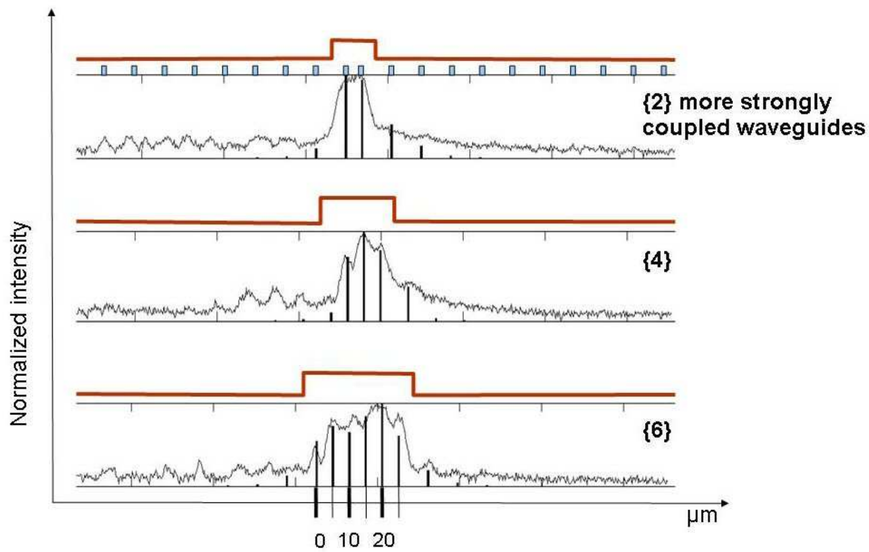

Fig. 4. Comparison of sections of the experimental output intensity images of Fig. 3 (solid gray lines) with the CMT results (taking a_m values only at the waveguide centers, shown as black vertical bars whose height represents the CMT intensity). Data are shown for a 8.75 µm wide injection in N more strongly coupled waveguides (designated by {N}) forming a channel of coupling constant $C_1=2C_2$. The sample is 3.4 mm long (i.e. ~5 coupling lengths in C_1 units). A schematic view of the channel (analog of a waveguide for photons) of increasing width is given above each subplot. The position of the centers of the ridges is indicated by the position of each bar of the CMT simulation. Additionally the positions of the corresponding ridges are shown at the top of the N=2 plot.

As can be seen, the CMT efficiently predicts the intensity of light in the output field. One can note that the theoretical predictions agree very satisfactorily with experimental output for {N=2}, {N=4}, and {N=6}. The predicted and experimental results for {N=8} are comparable, though irregularities of the signal within the channel are not well caught. Further discrepancies arise when fit of the {N=10} structure is attempted. Several reasons can be invoked to explain this: inadequateness of CMT in which only the first band with cosine shape is considered, or more probably slight tilt in the injection or defects/lack of homogeneity in the structure.

It may be noted that the size of the injection beam is kept constant at a value which for most cases is quite smaller than the channel width. In other words, there is a large mismatch between the fundamental mode of the channels and the injection beam. This leads to the excitation of many modes of the structure, both guided modes – rather near to the ones of perfectly confined channels described in section 2 – and leaky modes whose k_z lie in the barriers band, which can hence propagate in them, and which will be eliminated in the end by divergence – slower than in the channel – for long propagation paths, as in any conventional waveguide. In direct CMT simulations such as those reported in Fig. 4 (black vertical bars), all these effects are taken into account, but mode contributions are intermixed. Projection on the calculated modes show that guided propagation involves mostly the two highest even confined modes – those which have high amplitudes at the channel center – and that for our injection pattern and our propagation path they carry at least 80% of the injected power. The extension of evanescent waves is very small (~1 inter-guide spacing) and intensity outside the channel is mostly due to leaky modes.

Finally, Fig. 3 and Fig. 4 are the experimental demonstration of how patterning of the governing parameter C successfully leads to a discrete refractive optics function (here confinement of light) in structures that we can trust to be good realizations of the schemes elaborated with CMT.

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5. Conclusion and perspectives

We have thus demonstrated that patterning the coupling constant C in waveguide arrays results in a specific function of discrete diffractive optics: the light distribution within the array can be confined in custom-fabricated structured arrays where the coupling constant map is engineered to create the analog of a confining structure in the extensively studied photonic (waveguide) or electronic (quantum well) domains. We have strong indications that (i) CMT provides us with a simple tool for simulating light propagation in any array, and hence for designing more complex C-patterns and associated functions, and (ii) III-V technology enables us to realize these patterns.

Based on these foundations, it is clear that our demonstration of light confinement by patterning of the coupling constant is only the first building block of a whole "*discrete photonics*" world, where Floquet-Bloch waves can be manipulated at will. Similarly to what brought success to conventional and photonic-band-gap optics through optical index patterning, the flow of guided light can be molded in much more complex ways by structuring the coupling constant according to more elaborate patterns. The conceptual step from a uniform space to interfaces and superstructures can lead to many interesting passive and active signal processing functions already in the linear domain. It can also fertilize the original non-linear approach to control of light by light [10,24-26] by helping pump beam control, lowering threshold, or rely on control by external parameters. We have indeed already simulated [42,44] passive and active effects formerly obtained in usual photonics (redirecting, focusing, guiding, routing, etc.), now implemented in the discrete guided regime. Since the new properties and functions it addresses are actually based only on the coupling of waveguides, whatever the nature of the guided wave, a generic term for this field such as "*guidonics*" would perhaps be more descriptive.

Acknowledgments

We gratefully acknowledge support and fruitful advice from J.Y. Marzin and M. Bensoussan. These results are within the scope of C'nano IdF; C'nano IdF is a CNRS, CEA, MESR and Région Ile-de-France Nanosciences Competence Center.