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Nové směry v integrované optice

Novel Trends in Integrated Optics

Summary

Integrated-optic components and devices have already found interesting applications in broadband optical telecommunication systems, optical sensing, and microwave technology. However, many other complex high-performance guided-wave components and devices for access, metropolitan and local optical networks like fixed and tuneable filters, add-drop de/multiplexers, reconfigurable space switches, wavelength converters *etc.* that have been developed, still wait for their large-scale deployment. Their prohibitively high cost can be dramatically reduced only by batch fabrication of photonic devices with higher degree of integration. For this purpose, 'uniform' fabrication technologies that are much rarer in photonics than in microelectronics are to be applied, and the size of individual guided-wave devices integrated on an optical chip has to be reduced.

In this lecture, two kinds of novel photonic waveguide structures suitable for photonic integration are briefly presented. Ring and disk microresonators represent the more classical, "evolutionary" branch of development while waveguide devices in (two-dimensional) photonic crystals represent the "revolutionary" approach. We explain the principles of operation of some of these structures, show results of basic experimental characterization of one of them, and describe two methods for their numerical modelling that are connected with our own research activity in this field.

Efficient numerical modelling is of vital importance for design and development of these new components since it helps significantly reduce design time and costs. Most frequently used methods are based on *discretization* of coordinates (finite-difference or finite element methods and their modifications). In this lecture we will concentrate on the fundamentals of *modal methods* that are generally less flexible but, if correctly formulated, very accurate and often bring deeper physical insight into the pertinent wave processes. Two strongly related modal methods are presented: a two-dimensional mode expansion and propagation method for modelling optical field distribution propagating in guided-wave photonic devices, and a rigorous fully vectorial mode solver for straight and bent waveguides based on mode matching. The methods were developed within several national and international research projects with strong participation of PhD students, and their results have been currently applied in different MS and PhD courses. At the end, a link between research and education in guided-wave photonics and their integration into international environment in Europe is briefly discussed.

Souhrn

Mnohé struktury a součástky integrované optiky již našly zajímavé aplikace v širokopásmových optických telekomunikačních systémech, optických senzorech i mikrovlnné technice. Mnoho dalších velmi výkonných vlnovodných struktur a součástek pro přístupové, metropolitní i lokální optické sítě jako jsou pevné a laditelné filtry, vyčleňovací a začleňovací de/multiplexory, rekonfigurovatelné spínače, konvertory vlnových délek ap., které již byly vyvinuty, na své hromadné využití dosud čeká. Důvodem je jejich příliš vysoká vysoká cena. Ta může být výrazně snížena jen při hromadné výrobě součástek a struktur s vyšším stupněm integrace. Pro tento účel je třeba využít dostatečně „uniformní“ výrobní technologie, které jsou ve fotonice podstatně vzácnější než v mikroelektronice, a je třeba výrazně zmenšit rozměry jednotlivých fotonických struktur integrovaných na jednom optickém čipu.

Přednáška je věnována dvěma novým typům fotonických vlnovodných struktur vhodných pro fotonickou integraci. Kruhové a diskové mikrorezonátory představují klasičtější „evoluční“ vývojovou větev, zatímco vlnovodné struktury ve (dvojrozměrných) fotonických krystalech reprezentují „revolučnější“ přístup. Jsou objasněny základní principy funkce těchto struktur, ukázány základní výsledky experimentální charakterizace jedné z nich a popsány dvě metody jejich numerického modelování, které vycházejí z našeho vlastního výzkumu v této oblasti.

Efektivní numerické modelování má zásadní význam pro návrh a vývoj těchto nových struktur, poněvadž významně zkracuje dobu návrhu a snižuje náklady na vývoj. Nejčastěji jsou používány metody založené na *diskretizaci* souřadnic (metody konečných diferencí a konečných prvků a jejich modifikace). V této přednášce se soustředíme na použití *modálních metod*, které jsou sice obecně méně flexibilní, ale pokud jsou správně formulovány, jsou velmi přesné a zpravidla poskytují hlubší fyzikální pohled na zkoumané vlnové jevy. Zabýváme se dvěma úzce souvisejícími metodami, a to dvojrozměrnou metodou obousměrného rozkladu a šíření vlastních vidů pro modelování rozložení optického záření šířícího se ve vlnovodných fotonických strukturách, a rigorózní plně vektorovou metodou pro výpočet vlastních vidů v přímých a kruhově zakřivených vlnovodech, založenou na „sešívání vidů“. Metody byly vyvinuty v rámci několika národních i mezinárodních výzkumných projektů s významnou účastí doktorandů, a jejich výsledky jsou běžně využívány při přednáškách pro magisterské i doktorské studium. V závěru je stručně diskutována vzájemná vazba výzkumu a vzdělávání ve fotonice a jejich integrace do mezinárodního prostředí v Evropě.

Keywords

Integrated optics, photonics, optical waveguide, high refractive-index contrast waveguide, optical microresonator, two-dimensional photonic crystal, photonic crystal waveguides, eigenmodes, modal methods, mode matching method.

Klíčová slova

Integrovaná optika, fotonika, optický vlnovod, vlnovody s velkým kontrastem indexu lomu, optický mikrorezonátor, dvojrozměrný fotonický krystal, vlnovody ve fotonických krystalech, vlastní vidy, modální metody, metoda sešívání vidů.

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1 INTRODUCTION

Integrated optics was born at the end of the sixth decade of the last century as a new original discipline inspired by the tremendous progress of microelectronics and quantum electronics, as a promising complement of the nascent fibre optics and emerging optical communication. With some uncertainty, it could be characterized as a scientific and technological discipline dealing with components and devices that manipulate ("process" or "control") photon flow in planar or channel optical waveguides fabricated on a planar substrate, providing thereby some technically useful operations. During its more than 30 years of evolution, integrated optics passed through different stages – from its idea-driven beginnings in the seventies when a large number of different waveguide structures, devices, and their principles of operation were proposed, theoretically analyzed, and some of them also experimentally fabricated and tested, through the "technology-driven" period in eighties when many different fabrication technologies were significantly refined and improved, over the "application-driven" period in nineties when the development was mainly determined by the needs of potential users mainly in optical communication, in view of a "market-driven" development that was expected to come at the beginning of the 21st century. The drastical decrease of investments into optical telecommunication technologies in the first years after 2000 (well-known "telecom bubble") could not remain without a strong impact on the development in integrated optics: the most important parameter of any applicable integrated-optic component – regardless how demanding its technical specifications are – became its cost. Currently, too high prices of devices and components are prohibitive for most potential end users.

Cost can be dramatically reduced only by batch fabrication of photonic devices with higher degree of integration. For this purpose, 'uniform' fabrication technologies that are much more rare in photonics than in microelectronics have to be adopted, and the size of individual guided-wave devices integrated on an optical chip has to be reduced.

In this lecture, two kinds of novel photonic waveguide structures potentially suitable for photonic integration are briefly presented. Ring and disk microresonators are representative examples of a classical, "evolutionary" branch of integrated optics development. We explain the principles of operation of microresonator-based structures and show some of their application possibilities. The appearance of photonic crystals introduced a really revolutionary new approach into optics and photonics as a whole, and into integrated and guided-wave optics in particular. We will very briefly introduce principles of waveguiding in two-dimensional photonic crystals with envisaged applications in waveguide devices. In real structures, wave confinement in the third (vertical) dimension by index guiding will be assumed. Because of considerable complexity of underlying physics, only basic features of the structures will be tackled in this short lecture.

Efficient numerical modelling is an important part of design of these new and complex components since it helps significantly reduce design time and costs. Usually, methods based on *discretization* of coordinates (finite-difference or finite element methods and their modifications) are applied. In this lecture we will concentrate on the fundamentals of *modal methods* that are generally less flexible but, if correctly formulated, very accurate and often bring deeper physical insight into the pertinent wave processes. Two strongly related modal methods are treated here: a two-dimensional mode expansion and propagation method for modelling optical field distribution propagating in guided-wave photonic devices, and a rigorous fully vectorial mode solver for straight and bent waveguides based on mode matching. The methods were developed within several national and international research projects with strong participation of PhD students, and have been currently used in MS and PhD courses.

At the end, mutual linkage of research and education in guided-wave photonics and integration of research and education into international environment within the European 6FP Network of Excellence “ePIXnet” is briefly discussed.

2 NOVEL TRENDS IN GUIDED-WAVE PHOTONICS

Currently, one of the most popular integrated-optic devices is the arrayed waveguide grating demultiplexor (AWG) [1, 2] schematically sketched in Fig. 1.

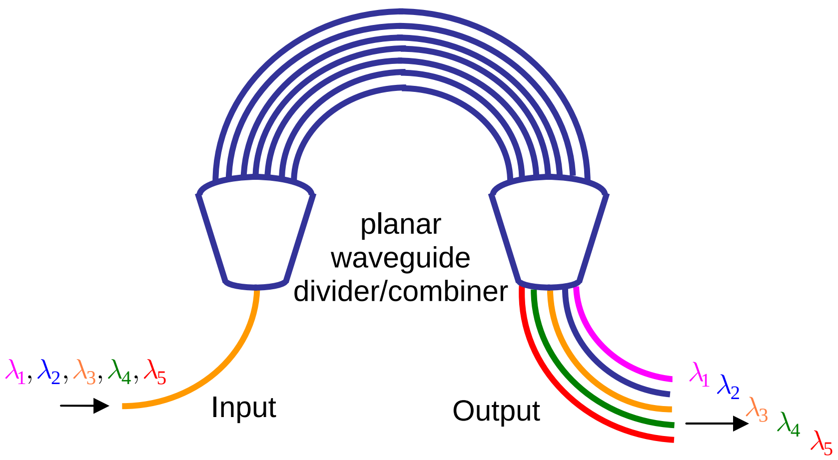

Fig. 1. Schematic configuration of the arrayed waveguide grating demultiplexor.

It is essentially a planar waveguide spectrum analyzer that relies on differential phase shift of modes propagating in channel waveguides of different length. Their application in optical communication systems with dense wavelength-division multiplex (DWDM) requires subnanometer spectral resolution; in the central optical telecommunication band around the wavelength of 1.55 µm, the standardized separation between two neighbouring wavelength channels is only 100 GHz, or equivalently, 0.8 nm. An example of a spectral transmittance of a 16-channel ARW demultiplexor is plotted in Fig. 2.

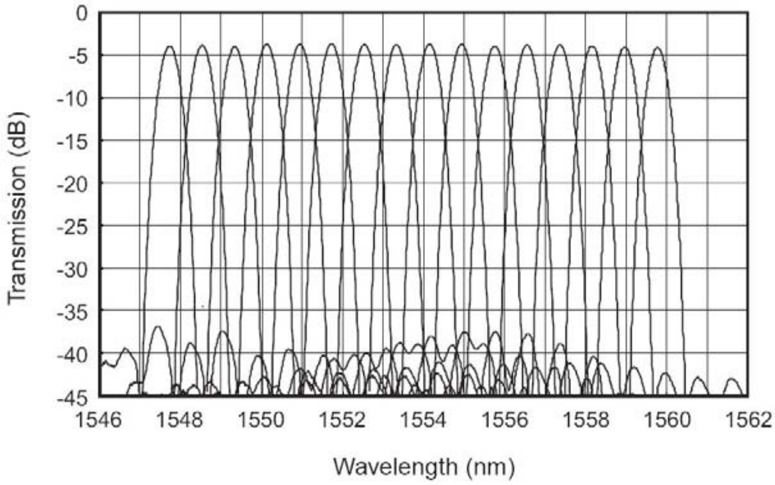

Fig. 2. Typical spectral characteristics of a 16-channel AWG demultiplexor [3].

Large number of various AWG designs have appeared not only in literature, but also on the market. The size of AWG devices strongly depends on the fabrication technology, or more specifically, on the refractive-index contrast of the waveguide structures. For low refractive index contrast waveguides like those made in glass or SiO_2, the total device area can be as large as hundreds or even thousands of mm^2 while high refractive index contrast structures like GaInAsP/InP or silicon on insulator (SOI) help reduce the total size of a whole device well below 1 mm^2. This strong dependence of the device area on the refractive index contrast comes mainly from the very strong dependence of radiation loss from waveguide bends on the refractive index contrast: with increasing contrast, the radiation loss decreases faster than exponentially. The waveguide divider/combiner sections are the most critical components of the devices since they determine the shape of spectral characteristics of the device and contribute to on-chip losses of the device.

Not only the size of devices depends on the refractive index contrast. Another important difference is in polarization properties of waveguides. Wave propagation in isotropic dielectric waveguides is generally governed by the vectorial wave equation

$$\Delta\mathbf{E} + \nabla\left[\nabla\left(\ln n^2\right)\cdot\mathbf{E}\right] + k_0^2 n^2 \mathbf{E} = \mathbf{0}, \qquad (1)$$

where $n^2(x,y)$ is the transversal refractive-index profile, $k_0 = 2\pi/\lambda$, λ is the free-space wavelength, and $\mathbf{E}(\mathbf{r})$ is the electric field distribution of the guided wave.

In weakly-guiding low-contrast waveguides, the second term in (1) can be neglected, and Eq. (1) simplifies to Helmholtz equation,

$$\Delta \mathbf{E} + k_0^2 n^2 \mathbf{E} = \mathbf{0}. \qquad (2)$$

As the components of $\mathbf{E}$ in (2) are mutually decoupled, the mode field can be considered (linearly) polarized and is thus describable in a good approximation by a single scalar function. As a result, although polarization dependence of weakly-guiding waveguides must be taken into account in critical applications, too, it is substantially weaker than in high contrast waveguide structures. The transverse dimensions of a single mode waveguide and the mode field size of weakly-guiding waveguides are close to that of a (weakly guiding) standard single-mode fibre, which results in small chip-to-fibre coupling losses. To keep a single-mode regime in high refractive index contrast waveguides, their transverse dimensions must be smaller than the wavelength. Rather sophisticated mode size transformers are usually required to increase the fibre-chip coupling efficiency of such high-contrast waveguides [4].

In the next parts we will briefly describe some novel ideas in the design of spectrally selective waveguide devices – the application of microresonators and photonic crystal devices.

2.1. Ring microresonator devices

Perhaps the most straightforward way to create a spectrally selective device is to use a resonator. In guided-wave optics, ring resonators are especially attractive; in contrast to Fabry-Perot resonators, they do not need waveguide mirrors that are much more difficult to fabricate than in bulk optics – it is sufficient to create just the closed-loop waveguide. For the coupling of the microresonator with the input/output waveguides, evanescent-wave coupling is used to advantage – it introduces negligible excess loss. An example of a basic unit of the microresonator device is shown in Fig. 3.

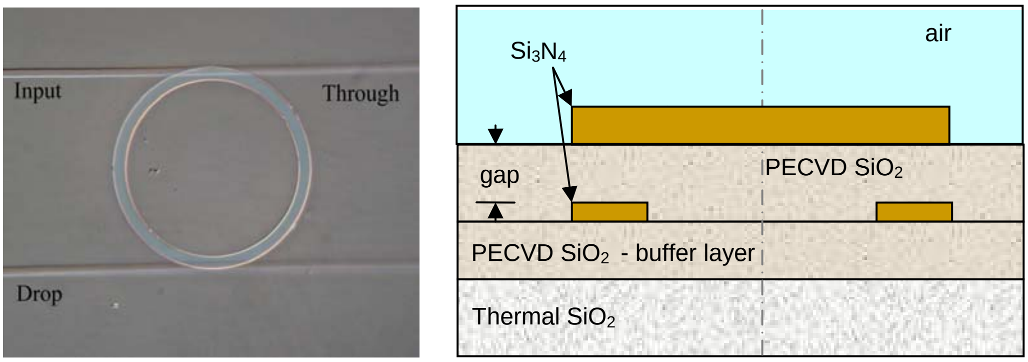

Fig. 3. Ring microresonator evanescently coupled to throughput and drop "port" waveguides. Left – microphotograph from an optical microscope, right – sketch of the vertical cross-section the device. The ring diameter is 50 µm, the ring guide cross-section is 2.5×0.3 µm, and the port guide cross-section is 2×0.14 µm.

The device was fabricated at the University of Twente in the framework of the EU project IST-2000-20218 "NAIS" (Next-generation Active Integrated-optic Subsystems) in which our laboratory participated.

The coupling gap between the ring and "port" waveguides often needs to be very small – of the order of tens or hundreds of nanometres – to ensure the necessary coupling strength along a short path. Two currently used arrangements of evanescent coupling – lateral and vertical coupling schemes – are schematically sketched in Fig. 4. Laterally coupled devices can be fabricated in a single microlithographic step, without the need of accurate alignment of subsequent masks. It is, however, very difficult to make the small coupling gap with the necessary accuracy and reproducibility. The vertical arrangement of mutually coupled waveguides has the advantage that the critical separation between the coupled waveguides is determined by the thickness of the intermediate layer, not by a microlithographic process, and can thus be more easily and accurately controlled. At least two microlithographic steps with a very accurate mutual alignment of masks are required, however.

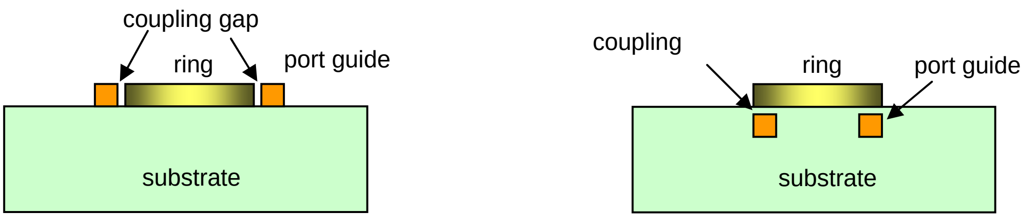

Fig. 4. Lateral (left) and vertical (right) coupling of the ring microresonator with the input/output "port" waveguides.

Spectral characteristics of the device can be calculated rather easily using the general theory of loaded microresonators (see, *e.g.*, [5]). In Fig. 5, a qualitative comparison of calculated and measured spectral characteristics is shown. Measured data were obtained in our laboratory using a recently built experimental setup for characterization of photonic waveguides and devices [6].

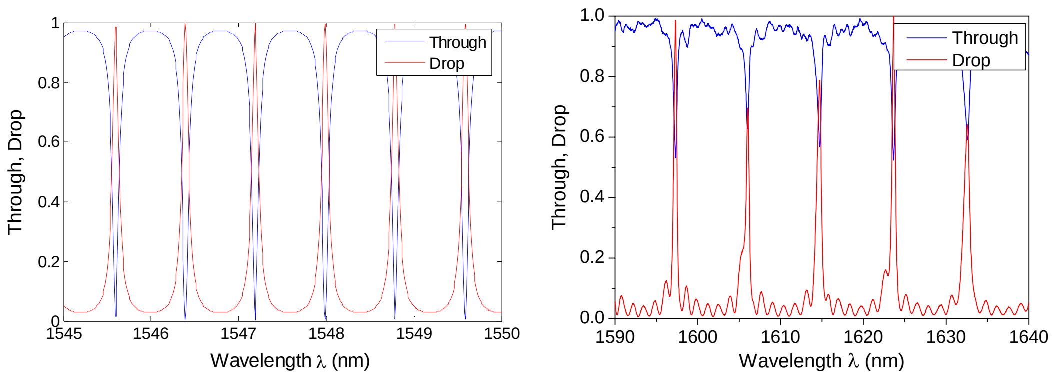

Fig. 5. Left: calculated relative throug and drop power for a microresonator with coupling factors $t_1 = t_2 = 0.85$, roundtrip loss 0.05 dB, and roundtrip path length 3000 μm. Right: measured characteristics of an experimental $Si/SiO_2/Si_3N_4$ microresonator.

The attractiveness of the microresonator-based devices is invoked mainly by the expectations that microresonators can be used as rather universal building blocks for large-scale photonic integration [7]. From Fig. 5 it follows that at resonance, optical signal is directed to the drop port while out of resonance it is lead to the throughput port. The microresonator can thus be used as a passive filter. Taking into account the possibility of thermo-optic, electro-optic or even "all-optic" tuning using $\chi^{(3)}$ optical nonlinearity of microresonators, operations like modulation, switching and routing using arrays of microresonators integrated on a single substrate seem to be feasible.

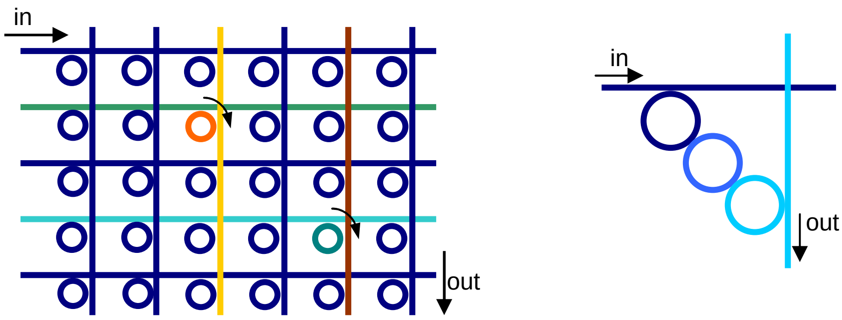

Fig. 6. Left: two-dimensional array of microresonators as a space switch. Right: third-order wavelength filter.

Schematic arrangements of a microresonator-based space switch and a wavelength filter are shown in Fig. 6. A number of other configurations have been proposed and experimentally tested, too. Interesting examples can be found in references [8-10]. Electro-optic and thermo-optic tunability of polymer-based ring microresonators has recently been analyzed in our recent study [11]. Our contribution to microresonator modelling will be described later in this lecture.

2.2. Photonic crystal waveguides and devices

The concept of a photonic crystal was introduced in 1987 in the classical paper of Yablonovitch *et al.* [12]. This paper has triggered a real avalanche of publications describing various aspects of photonic crystals, from their theoretical modelling over the fabrication approaches up to application possibilities in various fields of optics and photonics. In this situation, an attempt to briefly describe the impact of photonic crystals on integrated optics is really very challenging. For introductory reading, let us refer to "classical" books by Joannopoulos *et al.* [13, 14]. Theoretical fundamentals of waveguiding in photonic crystals are described in [15] for planar waveguides and in [16] for channel (linear) waveguides. Here we will concentrate only on optical waveguiding in two-dimensional (2D) photonic crystals.

To easily understand the basics, let us start with one-dimensional (1D) structures. A 1D "photonic crystal" is essentially a periodic stack of layers with alternating refractive indices. Although the theory of optical thin-films has been developed a few decades ago [17], many of its findings have been re-discovered and put into new context in the photonic crystal research environment. We will consider alternating layers of two different materials with refractive indices n_1 and n_2, respectively, as in Fig. 7.

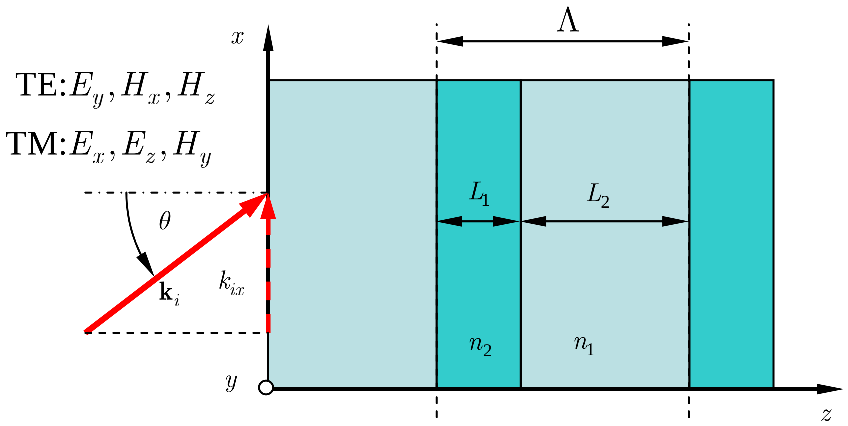

Fig. 7. Periodic stack of layers as a 1-D photonic crystal.

The plane wave incident on the stack from the left under the angle θ with the tangential wave vector component $k_{ix} = |\mathbf{k}_i| \sin\theta$ will excite plane waves propagating in the layers from left to right and from right to left with the same tangential wave vector component k_{ix} but with different longitudinal wave vector components $k_{1,2z} = \pm\sqrt{(k_0 n_{1,2})^2 - k_{ix}^2}$. From symmetry considerations it is evident that two independent polarization states propagate independently: transversally electric (TE) wave with the only nonzero field components E_y, H_x and H_z, and transversally magnetic (TM) wave with the only nonzero field components E_x, E_z and H_y. Considering for the moment only one polarization, two generally complex field amplitudes in each slab are required to describe completely the resulting field distribution in each slab.

Instead of two amplitudes of individual plane waves, we can equally well use two amplitudes of *Floquet-Bloch* (FB) *modes* defined as field distributions that are reproduced up to a constant multiplier if the z-coordinate is translated by a period Λ. We can thus write (*e.g.* for TE-polarized wave)

$$E_y^{\pm}(x, z + \Lambda) = \exp(\pm i k_{\mathrm{FB}} \Lambda) E_y^{\pm}(x, z), \tag{3}$$

where $E_y^{\pm}(x,z)$ are the field distributions of the forward (+) and backward (–) propagating Floquet-Bloch mode, and $\pm k_{\mathrm{FB}}$ are their respective propagation constants (wavenumbers). It is a bit cumbersome but straightforward to rewrite this condition into the form of a 2×2 matrix eigenvalue problem that can easily be solved analytically. Let us note that there is a one-to-one analogy between the field distribution of E_y of the TE-polarized wave and the distribution of the quantum mechanical wave function in the Kronig-Peney model of a periodic potential in solid-state physics. It is also important to realize that the FB modes are eigenmodes of a *single period* of the periodic structure, and can thus be applied to describe field distribution in *finite* as well as in *infinite* periodic structures equally well. From (3) it also follows that the propagation constant k_{FB} is determined up to the additive constant $K = 2\pi / \Lambda$; it holds $\exp\left[\pm i\left(k_{\mathrm{FB}} + K\right)\Lambda\right] = \exp\left(\pm i k_{\mathrm{FB}}\Lambda\right)$. The propagation constant k_{FB} can thus always be chosen from the interval $\left\langle -K/2, K/2\right)$, *i.e.*, from the *first Brillouin zone* of the (1D) k-space.

Equation (3) determines the relation between the frequency of the wave ω (or its free-space wavelength $\lambda = 2\pi c / \omega$) and the propagation constant k_{FB}, *i.e.*, the *dispersion relation* of the FB mode. An example of such a diagram is shown in Fig. 8. Blue lines show spectral regions where k_{FB} is real, red lines show $\pm\left|k_{\mathrm{FB}}\right|$ for imaginary values of k_{FB}.

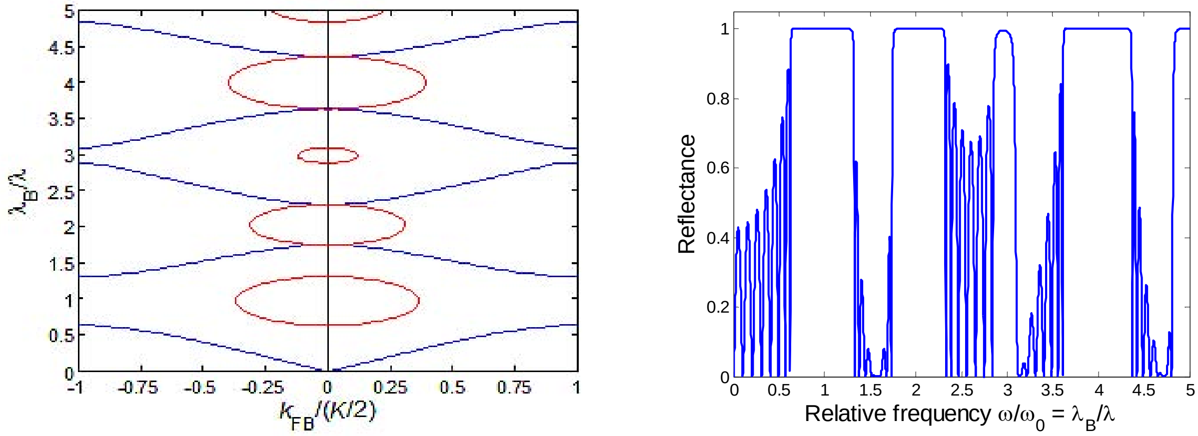

Fig. 8. Left: dispersion (band) diagram of a 1D periodic stack of layers with refractive indices $n_1 = 1, n_2 = 3.5$ and thicknesses $L_1 = 0.3$ μm, $L_2 = 0.15$ μm. TE polarization, $\theta = 0°$ (perpendicular incidence). Right: Spectral dependence of reflectance of the stack of 7 periods.

We see that k_{FB} is imaginary for λ in the vicinity of integer fractions of the Bragg wavelength $\lambda_{\mathrm{B}} = 2(L_1 n_1 + L_2 n_2)$ of the structure. It means that in these wavelength regions, the FB modes are evanescent (damped) in the direction of propagation. The incident wave can thus partially penetrate through a photonic crystal of finite length but is totally reflected back from a half-infinite photonic crystal. These spectral regions form the “photonic forbidden gaps”, or “bandgaps” of the photonic crystal. In words of “classical” wave optics, bandgaps are regions where the waves experience first- or higher-order Bragg reflections. Bandgap is the wider the larger is the refractive-index contrast of the periodic structure.

The fact that the waves within the bandgaps are reflected back from the crystal can be used to create a planar waveguide: instead of total internal reflection at the interfaces we can use the total reflection from the stack of layers. We thus arrive to the concept of a “defect waveguide” formed by a “defect” in an otherwise perfectly periodic structure, as shown in Fig. 9.

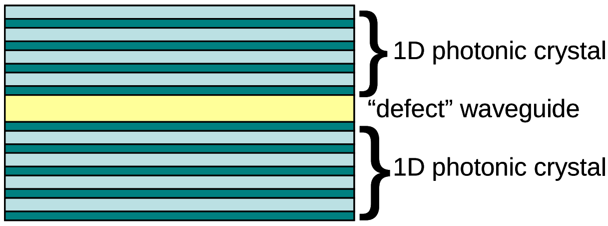

Fig. 9. “Defect” planar waveguide in a 1D photonic crystal.

It is interesting to note that this type of waveguides has been known in integrated optics for almost two decades as an ARROW waveguide (antiresonant reflecting optical waveguide) [18]. Its advantage is that the refractive index of the core (the central guiding layer) can be *lower* than one or both refractive indices of the layers that form the (Bragg) mirrors. If the wave propagates in the direction perpendicular to the interfaces, we get a 1D resonant cavity with two (Bragg) reflectors. In the photonic crystal terminology we speak about “wave localization by defect” or about a “1D microcavity”.

A 2D periodic array of holes “drilled” into a high-index material shown in the left part of Fig. 10 is a typical example of a 2D photonic crystal with hexagonal symmetry. One possible choice of a primitive cell of the structure is marked by the yellow hexagon. Any other cell can be obtained by the translation of the original hexagon by a vector $\mathbf{t} = m_1\mathbf{a}_1 + m_2\mathbf{a}_2$, where m_1 and m_2 are integers.

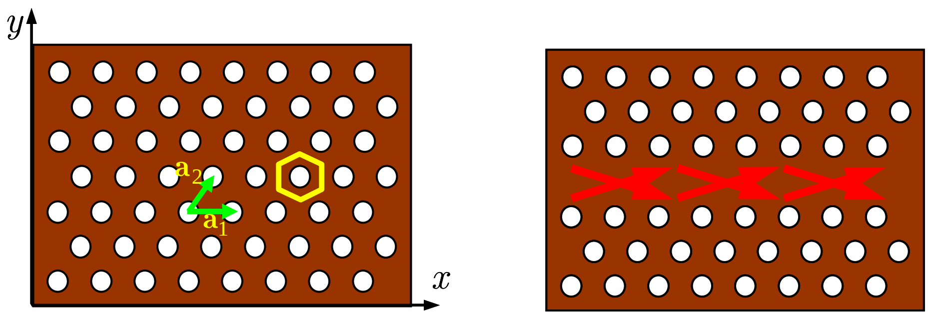

Fig. 10. Left: a 2D photonic crystal created by a triangular array of holes. Right: a “line defect” (channel) optical waveguide in a 2D photonic crystal.

Similarly as before, the FB mode can be found as a solution of Maxwell equations that reproduces itself up to a complex multiplier $\exp(i\mathbf{k}_{\mathrm{FB}} \cdot \mathbf{t})$ by the translation of coordinates by $\mathbf{t}$. Again, the FB mode is essentially an eigenwave of *a single cell*, and can thus be efficiently used for modelling finite as well as infinite (or semi-infinite) photonic crystals.

Because of the two-dimensional periodicity, the dispersion diagram relating $\mathbf{k}_{\mathrm{FB}}$ with the wavelength (or frequency, as in) of the propagating wave is much more complex. It can be calculated *e.g.* by the plane-wave expansion method [19]. The characteristic points K and M of the first Brillouin zone correspond to directions of propagation along the x and y coordinate axes (or their equivalents following to photonic crystal symmetry).

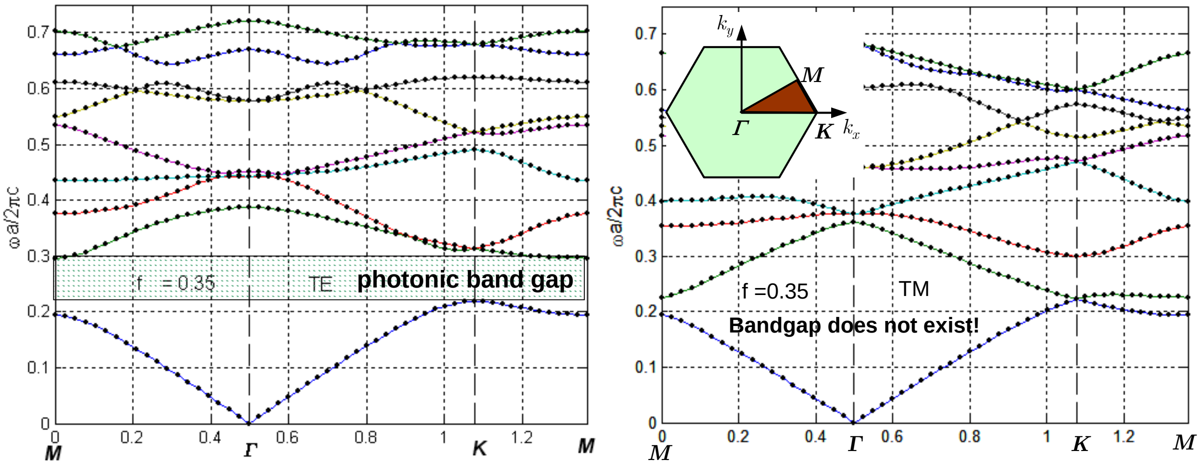

Fig. 11. Dispersion diagram of a 2D photonic crystal shown in the left part of Fig. 10. Left: TE polarization, right: TM polarization. The first Brilouin zone is depicted in the inset to the right graph. a is the pitch length, $a = |\mathbf{a}_1| = |\mathbf{a}_2|$, the refractive indices of the material and hole are 3.5 and 1, respectively, and the the ratio between the surface of the hole and of that of the primitive cell (air filling factor) is $f = 0.35$.

While there is no bandgap for TM polarization (electric field intensity parallel to the axes of holes), TE polarization exhibits a complete gap, *i.e.*, the optical wave cannot propagate at any direction and is (totally) reflected from the crystal. Similarly as in a 1D case, this feature can be used to create a "defect" waveguide in the 2D crystal, as it is schematically shown in the right part of Fig. 10. As it is shown in the right part of Fig. 8, sufficiently high reflectance can be reached even with a comparatively "thin" photonic crystal. Therefore, only a few rows of holes at each side of the waveguide might be sufficient to act as an almost perfect reflector.

For practical applications, the optical wave in the photonic crystal waveguide should be also confined in the third (vertical) dimension. Although in principle it is possible to use a 3D photonic crystals with the full photonic gap, this approach is hardly manufacturable with present technologies. Instead, a conventional "index guiding" can be used, as schematically depicted in Fig. 12.

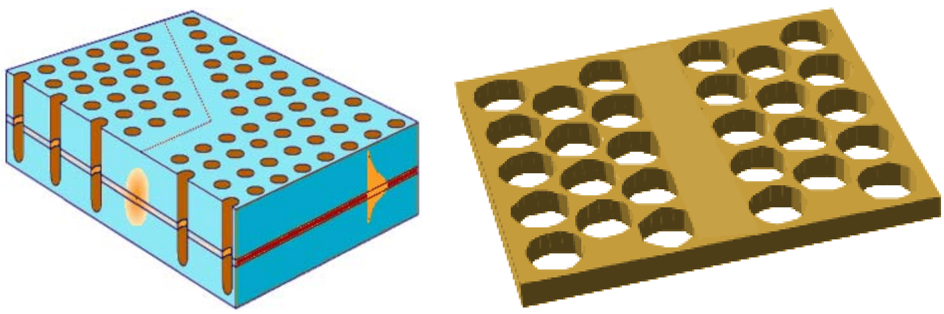

Fig. 12. Channel waveguides in 2D photonic crystals with vertical light confinement by index guiding. Left: planar slab waveguide. Right: suspended membrane waveguide.

Instead of translational invariance typical for standard waveguides, these waveguides are *periodic* along the direction of propagation. A typical feature caused by this periodicity is the possible appearance of a ministopband (minigap) in the transmission band of the waveguide [20]. On the other hand, complicated dispersion behaviour of such waveguides can be utilized in the design of photonic crystal waveguide devices like spectral filters, add-drop multiplexers, *etc.* [21-24]. Although a considerable amount of knowledge on these complex photonic structures has been gathered so far, a number of rather fundamental questions still remain to be answered. One of the most fundamental is the problem of radiation and scattering losses that is strongly related to deviations of the real structures from ideal periodic ones. Nevertheless, propagation losses as low as 1.8 dB/mm have recently been reported [25].

3. MODELLING NOVEL WAVEGUIDE DEVICES

As it has already been mentioned, numerical modelling of advanced waveguide devices has become an essential and inevitable part of their design. While the previous section was conceived more as a general introductory tutorial, in this section we concentrate mainly to our own research activity in the field.

Two variants of 2D modal methods have been treated in our research group within last years. One of them concerns the calculation of optical field distribution *along* the direction of propagation of optical waves in structures whose transverse coordinates can be reduced to a single one. The method is known as bidirectional eigenmode expansion and propagation method, or BEP. The second one is dedicated to calculation of fully vectorial field distribution of eigenmodes and their propagation constants in straight and bent waveguides and circular ring and disk microresonators. Principles and results of the methods will be briefly described in the next parts.

3.1. Mode expansion and propagation method

This method represents a very straightforward application of the mode matching method to a problem of wave propagation in waveguide structures with significant back-reflections. Its principles were very briefly described in [26]. We have developed this method for modelling waveguide surface plasmon sensors [27], waveguide gratings [28], and their combinations [29, 30]. More recently it has also been applied for modelling 2D photonic crystal structures [31, 32]. For efficient modelling of waveguides in periodic structures, the expansion into the Floquet-Bloch modes of the period has been used as an alternative to the expansion into local eigenmodes.

The principle of the method can be easily understood using the schematic view of the waveguide structure in Fig. 13. The analyzed waveguide structure is subdivided into a finite number of longitudinally uniform sections – waveguide *segments*. If a sequence of segments is repeated for several times, it is referred to as a *period*.

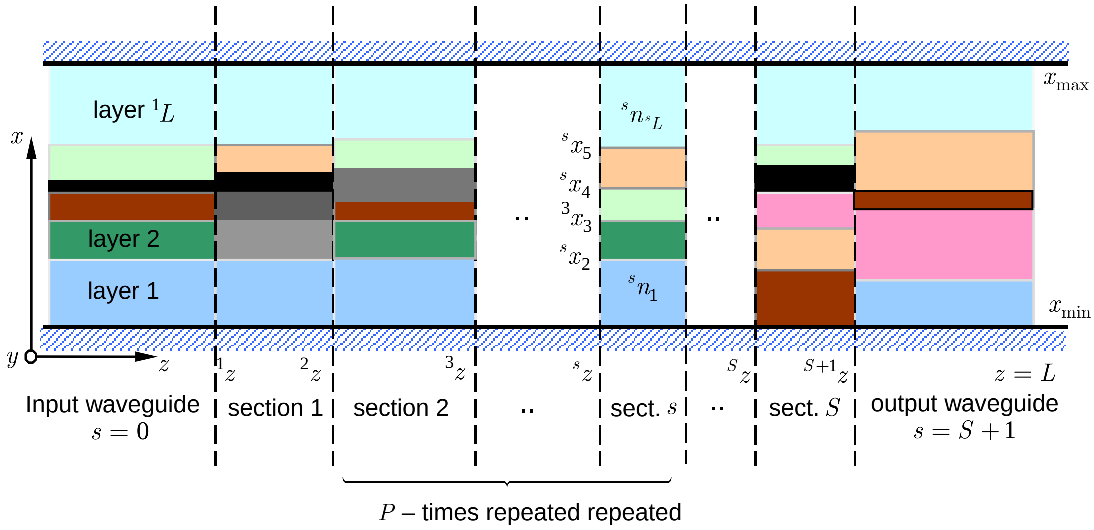

Fig. 13. 2D waveguide structure consisting of longitudinally uniform sections.

The first segment is an input segment, the last one the output segment. They are supposed to be infinitely long. In vertical direction, the structure is confined by electric or magnetic walls positioned in Fig. 13 at $x_{\min}$, $x_{\max}$. Alternatively, perfectly-matched layers represented by complex coordinates of boundaries [33, 34] can be applied. Our task is to calculate the (2D) field distribution in the whole structure having known the distribution of the wave incident from the left.

Each segment is considered as a finite stack of layers whose set of (TE or TM) eigenmodes can be easily calculated using *e.g.* the transfer matrix method [35]. Due to the implementation of horizontal walls, the eigenmode spectrum is discrete. The mode sets are calculated for each segment of the structure.

For the calculation of the field distribution in the whole structure, the immittance method known for its numerical stability [36] is used. Its principle can be easily explained by the analogy of the waveguide structure in Fig. 13 with the concatenation of segments of transmission lines (*e.g.*, coaxial cables) with different characteristic impedances. The field distribution in each segment is given by the superposition of (all) its forward and backward propagating modes. To find the backward propagating mode in the input segment, the reflection coefficient at the input interface is to be known. It can be easily calculated if we know the "loading impedance" of the input section. It can be calculated by successive transformations of impedances starting from the output waveguide towards the input using the formula for impedance transformation by a transmission line (in microwave engineering it is well-known as a "Smith diagram method"). Having calculated the amplitudes of backward propagating modes at the input, the total field can be calculated successively from the input to the output using the field continuity conditions at the interfaces between the segments. For periodic structures, the FB modes are calculated as eigenmodes of the transfer matrix of a single period, the mode amplitudes are transformed into the space of FB modes, and the procedure is then applied to the periodic structure as a whole. The details of the calculations can be found in [28]. This algorithm was used to get results published in [27-32, 37, 38].

Let us mention here only the comparison of modelling methods for 1D large-contrast periodic structures performed within the framework of European action COST 268 "Wavelength-scale photonic components for telecommunications" known as the "COST 268 task".[38]. Six methods developed independently in European research laboratories were used to calculate the spectral dependence of modal transmission and reflection of a deep waveguide grating, and their performance and results were mutually compared. In addition, radiation losses of the deep grating were studied to better understand the mechanisms of out-of-plane radiation losses in 2D photonic crystal waveguides.

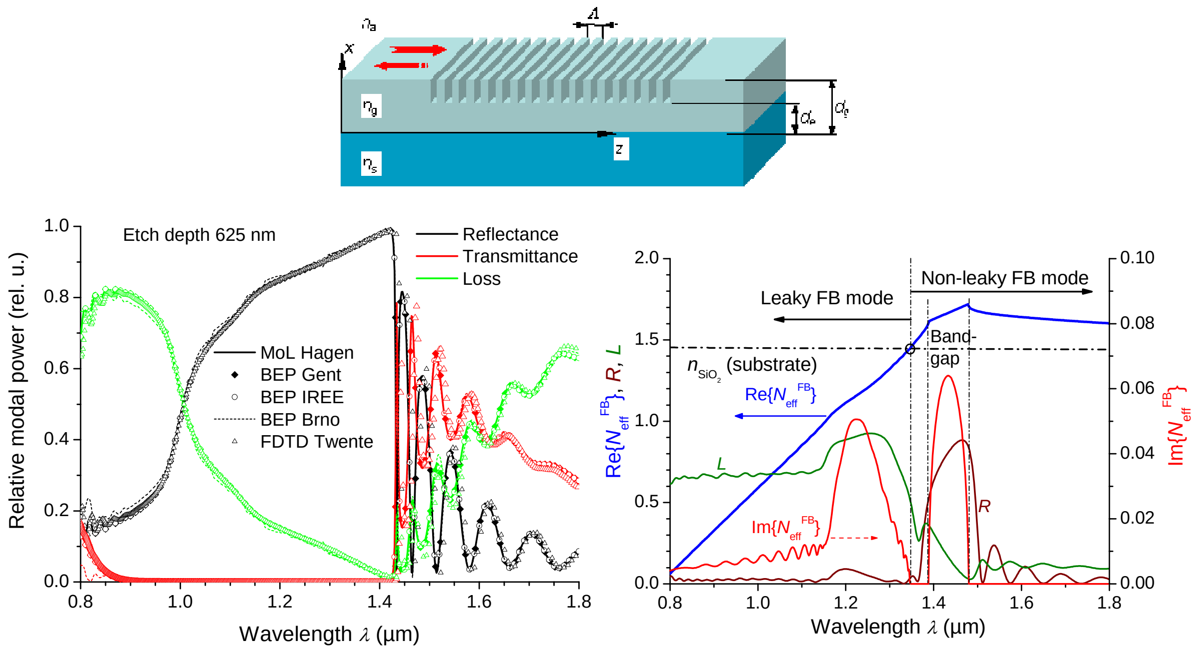

Fig. 14. Top: geometry of deeply etched grating with a period of 430 nm in SiO_2/Si_3N_4 waveguide. Waveguide layer thickness is 500 nm. Bottom left: modal reflectance, transmittance and loss of the grating with 20 periods with the etch depth of 625 nm calculated by 5 methods. Bottom right: Spectral dependence of the effective refractive index N_{eff}^{FB} of the FB mode, modal reflectance R and loss L for the grating with the etch depth of 250 nm.

Nearly perfect agreement of results of several fundamentally different methods is a rather convincing indication of their correctness. The spectral dependence of the effective refractive index of the FB mode in Fig. 14 clearly shows that the FB mode propagates without (significant) loss as long as its effective refractive index is larger than the refractive index of a substrate. (the mode is "below the light line" of the structure).

We have tried to apply our BEP method for modelling "line defect waveguides" in 2D photonic crystals, too, but its numerical stability appeared not to be high enough for this application. The stability can be improved by implementing more stable algorithms for the calculation of FB modes like the scattering or reflectance matrix formalisms [39].

3.2. Vectorial eigenmode solvers

In this section, our recent contribution to modelling microresonator-based devices is briefly reviewed. For “system modelling” of microresonator devices, parameters like coupling constants between the resonator and the input/output waveguides, phase and group propagation constants of both the ring and straight guides, free spectral range and radiation loss of resonators must be calculated with a reasonable accuracy. As the first step to calculation of all these parameters, a reliable vectorial mode solver for microresonators and bent waveguides is required. Such a mode solver has recently been developed in our group within the framework of the EU project “NAIS” as a topic of the PhD thesis of L. Prkna [40].

The developed mode solver is based on mode matching, and as such, it is essentially rigorous, without the need of any discretization. Prior to explain the fundamentals of the 3D mode solver let us consider the 2D case that allows elucidating basic features of ring resonators in a simpler way. We will consider 2D waveguiding structures schematically depicted in Fig. 15.

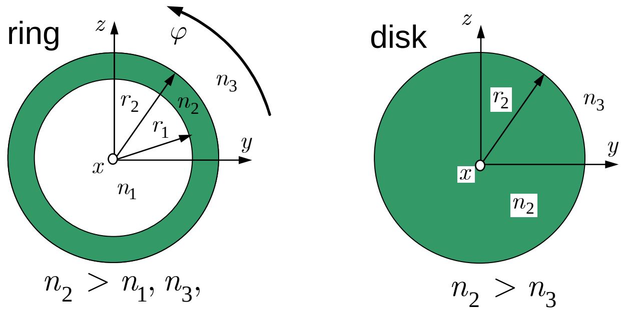

Fig. 15. 2D ring and disk microresonators.

There is an important difference between the straight and circularly bent waveguides that should be noted. As the straight waveguides are invariant with respect to translation along the waveguide direction z, the longitudinal dependence of their eigenmodes has the form $\exp(i\beta z) = \exp(ik_0 N z)$, where β is the propagation constant, and $N = \beta / k_0$ the effective refractive index of the mode. In circularly bent structures like those in Fig. 15, the structure is invariant with respect to rotation around the centre. As the mode field propagates in azimuthal direction, its dependence must be of the form $\exp(i\nu\varphi)$. Denoting the bending radius as R and realizing that the propagation length along the radius R is $R\varphi$, one can write $\nu\varphi = k_0 N R\varphi$, and thus $N = \nu / (k_0 R)$. But only ν is the true (azimuthal) propagation constant, while N depends on the choice of R (*e.g.*, from the centre to the inner or outer edge, or to the centre of the strip guide). Thus, for bent waveguides and microresonators, the concept of the effective refractive index of a mode looses its physical sense. Due to radiation from the bend, field propagates along the bent guide with attenuation. The azimuthal propagation constant ν of the bent waveguide is thus *complex*.

Modes of two polarizations can propagate in the 2D structures in Fig. 15: TE modes with field components E_x, H_r, H_φ, and TM modes with components H_x, E_r, E_φ. Because of cylindrical symmetry, the radial dependence of the fields has to satisfy Bessel equation in each radially uniform section of the structure. Thus, the electric field intensity of the TE mode can be written as

$$E_x(r,\varphi) = \begin{cases} AJ_\nu(k_0 n_1 r) & \text{for } r < r_1, \\ -BJ_\nu(k_0 n_1 r) - CY_\nu AJ_\nu(k_0 n_1 r) & \text{for } r_1 < r \le r_2, \\ DH_\nu^{(1)}(k_0 n_3 r) & \text{for } r > r_2, \end{cases} \tag{4}$$

where J_ν, Y_ν and $H_\nu^{(1)}$ are the Bessel function, the Neumann function, and the Hankel function of the first kind, respectively. From the field continuity conditions we easily find that the amplitudes A, B, C, and D must satisfy the set of linear equations

$$\mathbf{L}(\omega,\nu) \cdot \begin{pmatrix} A & B & C & D \end{pmatrix}^T = \mathbf{0}, \tag{5}$$

where

$$\mathbf{L}(\omega,\nu) = \begin{pmatrix} n_1 J_\nu'(n_1\rho_1) & n_2 J_\nu'(n_2\rho_1) & n_2 Y_\nu'(n_2\rho_1) & 0 \\ J_\nu(n_1\rho_1) & J_\nu(n_2\rho_1) & Y_\nu(n_2\rho_1) & 0 \\ 0 & n_2 J_\nu'(n_2\rho_2) & n_2 Y_\nu'(n_2\rho_2) & n_3 H_\nu^{(1)\prime}(n_3\rho_2) \\ 0 & J_\nu(n_2\rho_2) & Y_\nu(n_2\rho_2) & H_\nu^{(1)}(n_3\rho_2) \end{pmatrix}, \tag{6}$$

and $\begin{pmatrix} A & B & C & D \end{pmatrix}^T$ is the column vector with the elements A, B, C, D. To get a nontrivial solution, the determinant must be equal to zero,

$$\det[\mathbf{L}(\omega,\nu)] = 0. \tag{7}$$

This is the dispersion equation for the TE modes [41].

Although these formulas look relatively simple, their numerical evaluation is not trivial. The dispersion equation is to be solved for the (complex) *order* of cylindrical functions, but no reliable algorithms are available for such functions in software libraries. Moreover, the products of cylindrical functions and their derivatives in the determinantal equation lead often to numerical expressions of the type "$0 \cdot \infty$". Thus, special computer code had to be developed not only for cylindrical functions and their derivatives but also for their products, for which exponential scaling of functions had to be used. For these purposes, uniform asymptotic expansions [42] were used.

As it has been analyzed in some detail in [43], the dispersion equation (7) can be considered either as a dispersion equation for modes of a bent waveguide, or as a dispersion equation for modes in a circular resonator. In the first case the frequency in Eq. (7) is simply the frequency of the field propagating in the waveguide, and Eq. (7) is to be solved for the *complex azimuthal propagation constant* ν. In the second case, the symmetry (in other words, the condition of field selfconsistency in the whole ring resonator) requires that ν is an *integer*; then Eq. (7) is to be solved for the *complex frequency* ω. The real part of the complex frequency then gives the resonant frequency and the imaginary part determines the quality factor, $Q = -\mathrm{Re}\{\omega\}/(2\,\mathrm{Im}\{\omega\})$. The difference in the calculated field distributions in a microresonator with the radius of 10 μm using both approaches is apparent from Fig. 16. Note the strong wavefront bending due to radiation.

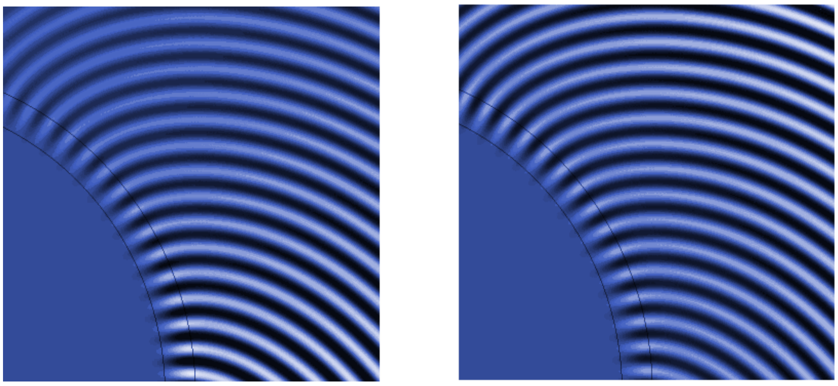

Fig. 16. Field distributions in a 2D bent waveguide (left) and a microresonator (right). Radius of curvature 10 μm, waveguide width 1 μm, $n_1 = n_3 = 1.6$, $n_3 = 1.7$, wavelength 1.55 μm.

Let us now turn our attention to 3D structures. The cross-section of a bent rib waveguide that forms a ring resonator is sketched in Fig. 17.

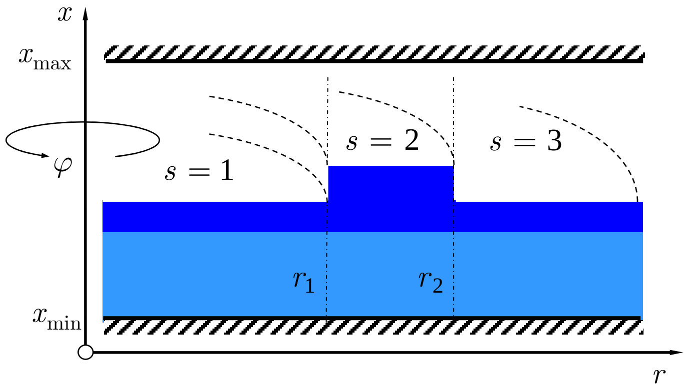

Fig. 17. Cross-section of a ring microresonator.

The modal approach to find eigenmodes of the structure is quite similar to that used in the BEP method. For straight waveguides it has been described by Sudbø [44, 45]. Each radially uniform section ("slice", denoted by $s = 1, 2, 3$ in Fig. 17) forms a multilayer waveguide. Artificial walls (electric, magnetic or perfectly matched layers) are placed below and above the structure to discretize the spectrum of its eigenmodes. Contrary to the case of a BEP method, the set of *both* TE and TM modes must now be calculated in each slice. They are required to describe the total field in the slice. All modes are expected to propagate in the azimuthal direction with the same (azimuthal) propagation constant ν. At each interface between the slices, tangential components of electric and magnetic fields ($E_\varphi, E_x, H_\varphi, H_x$) must be matched. From these constraints, a set of linear equations for complex amplitudes of individual modes of the slices can be constructed. However, an immittance approach [45] modified for cylindrical geometry has been chosen to improve the numerical stability of the procedure and to reduce the size of the problem. It is similar to that used in the BEP method but now the immittance matrices at the innermost and outermost slices can be determined from the boundary conditions, supposing that no wave is incoming from outside. The immittance matrices can then be transformed from both inner and outer slices to some intermediate interface where the eigenmode field is expected to be strong (*i.e.*, $r = r_2$). By equating them we arrive to a nonlinear eigenvalue problem for the propagation constant (and a linear one for the eigenmode field distribution). Its numerical solution is substantially more complicated than that of a 2D problem, but we succeeded to overcome most of the difficulties. A working mode solver has been created and successfully tested by comparison with two commercial software packages. The details have been described in the PhD thesis [40] and in recent publications [46-49].

Let us conclude this section with few examples of calculated eigenmode field distributions of microresonator devices in Fig. 18 and Fig. 19.

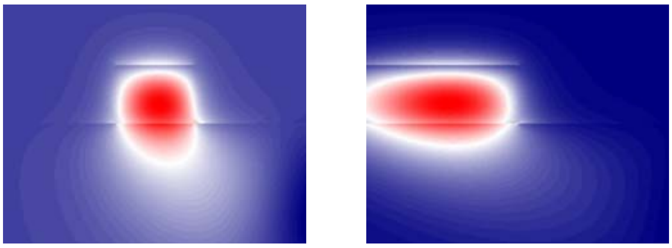

Fig. 18. Dominant component (E_x) of the TM_{00} mode of the ring (left) and disk (right) polymer microresonator with the outer radius of 50 µm.

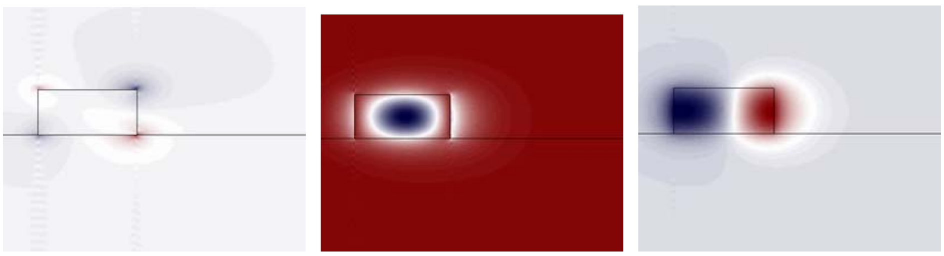

Fig. 19. Electric field components E_x, E_r, E_φ of the TE_{00} mode of a SiO_2/Si microresonator with the outer radius of 2.25 µm, ring width of 0.5 µm and height of 0.36 µm.

It has been verified that the mode field distribution calculated by this method can be utilized as an input field for the coupled-mode theory of a microresonator devices developed at the University of Twente within the NAIS project. The field distribution at three different cross-sections of a microresonator coupled to a straight waveguide calculated with the help of the coupled-mode theory is shown in Fig. 20.

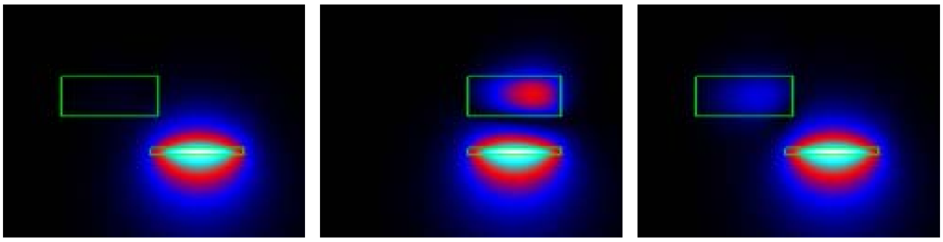

Fig. 20. Field distribution at three cross-sections of a vertically coupled microresonator device. The outer figures are taken at the positions ± 24 μm off the central cross-section (at the input and output of the device, respectively).

4. RESEARCH AND EDUCATION IN INTEGRATED OPTICS

As a concluding remark, let us briefly comment on mutual relations of research and education in integrated optics in our environment.

Our research group at IREE AS CR has been working in integrated optics for more than 25 years. Rather strong collaboration was soon established with Tesla Research Institute of Telecommunications (VUST), in which technological issues were solved mainly in Tesla, and our group was concentrated mainly on theory, design, and characterization of structures and devices. From the very beginning, our group had very frequent contacts with universitites, especially with the Czech Technical University in Prague, Faculty of Nuclear Science and Physical Engineering and Faculty of Electrical Engineering (CTU FNSPE and FEI), with the Charles University in Prague, Faculty of Mathematics and Physics (MFF CUni), and with the University of Chemical Technology in Prague, Institute of Chemical Technology (VSCHT). Individual lectures on integrated optics for MS and PhD students of these and some other Czech universities were regularly read, and these contacts ocassionally evolved into diploma and PhD theses. After VUST had ceased to exist in early nineties, some of its key researchers in optoelectronics continued their work at universities, mainly FEI CTU and VSCHT, and our contacts with those universities were considerably strengthened. Within last years, our research group participated in a number of national and several international projects jointly with partners and collaborators from universities, and new proposals of such projects are pending.

At present, new research results in the field of guided-wave optics are currently being incorporated into regular semestral courses of Integrated Optics. In view of the latest development in guided-wave optics, especially in high-refractive index contrast waveguide devices, photonic crystals and possibly also guided-wave plasmonics [50, 51], fundamental changes of the content of the courses of Optoelectronics and Electrodynamics 2 are now under serious considerations. Problems of guided-wave optics become ever more frequently topics of student research projects, diploma and PhD theses. Talented students are not only the most active members of our research teams in national as well as international projects but they also help organize important international meetings and conferences like recent prestigious 11th European Conference on Integrated Optics (ECIO'03) co-located with International Workshop on Optical Waveguide Theory and Numerical Modelling (OWTNM'03) in April 2003 in Prague. Participation in international projects and actions helps open additional possibilities for students to find suitable post-doc positions in leading European research laboratories.

Recently started new European 6FP NoE activity "ePIXnet" (European Network of Excellence on Photonic Integrated Components and Circuits) offers rather unique chances to all its partners, including our laboratory, for junior (student) exchange with the best European research teams and for access to their unique technological and experimental facilities. Moreover, rather strong interaction among partners is expected in the preparation, sharing and unification of courses and lectures in guided-wave optics, optoelectronics and related topics, aimed at good comparability of BC, MS, and PhD degrees in this field in the EU. One of the challenging goals might also be the creation of a "virtual" Internet library of the best courses and lectures, with direct on-line access to the corresponding educational texts, presentations, and seminar tasks. We are convinced that that our students would benefit a lot from any real progress in this area if it happens.

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CURRICULUM VITAE

Education and degrees:

Ing. in Microwave Engineering, 1968, Czech Technical University in Prague,
CSc. in Applied Physics, 1972, Czech Technical University in Prague,
DrSc. in Electronics, 1990, Czechoslovak Academy of Sciences, Prague,
Assoc. Prof. in Physical Electronics, 1999, Czech Technical University in Prague.

Career/Employment:

– 1972-73 Czech Technical University, Assistant Professor;
– since 1973 Institute of Radio Engineering and Electronics, Czechoslovak Academy of Sciences (Academy of Sciences of the Czech Republic), Prague;
– 1973 research scientist;
– 1978-2002 Head, Dept. of Guided-Wave Optics;
– since 1994 lecturer, (since 1999 associate professor), Czech Technical University, Faculty of Nuclear Science and Physical Engineering;
– since 1999 Deputy Director of Institute of Radio Engineering and Electronics.

Research Fellowships and visits

– 1979, 3months, Institute of General Physics, Soviet Academy of Sciences, Moscow, integrated optics;
– 1983, 1 month, Universität Dortmund, Germany, DAAD research fellowship in integrated optics
– 1984, 2 months, International Centre for Theoretical Physics, Trieste, Italy, Intenational School on Physics of Electronic and Optoelectronic Devices
– 1985-86 and 1991, 15 months, Universität Dortmund, Germany, A. von Humboldt research fellowship in integrated optics

Field of work

(i) dominant field
integrated optics, guided-wave optics, photonics

(ii) other fields
optoelectronics, electromagnetic field theory

(iii) current research interest
theory, modelling and characterisation of passive and nonlinear-optic guided-wave photonic devices; waveguides in photonic crystals; physics of surface plasmon sensors; optical microresonators and microresonator devices.

Regular semestral lectures

Fundamentals of Quantum Electronics, FEI CTU, winter semester, 2 h, 1973-1974;
Optoelectronics (together with J. Schröfel), FEI CTU, winter semester, 2 h, 1993 – 2003;
Electrodynamics 2, FNSPE CTU, summer semester, 4 h, since 1994;
Integrated Optics, FNSPE CTU + FEI VUT + FMP UK, winter semester, 2 h, since 1995 (since 2003 in English);
Optoelectronics FNSPE CTU, sumer semmester, 4 h, 1993 – 2003 with J. Schröfel and M. Kucharski, in 2004 with M. Karásek a J. Homola (in Eanglish);
Crystallo-optics, electro-optics, acousto-optics, PhD course, FNSPE and FEI CTU, 2 h, since 1995.

Publications and citations

– Number of papers in refereed journals: over 50;
– Number of communications to scientific meetings: over 50;
– Books: co-author of 2 books in Czech,
contributor and editor of 1 book in English;
– Patents: co-author of 12 patents;
– Citations: over 300 records in the ISI (Web of Science);

Research and organizational activities

Coordinator of the Czech participation in three EU research projects, coordinator of a number of national research projects;
Chair of ECIO'03 Conference, regular member of its Steering Committee;
Member of Steering Committee of the series of International Workshops on Optical Waveguide Theory and Numerical Modelling,
chair/co-chair of workshops held in Prague, Czech Republic, in 2000 and 2003;
JOSA A Topical Editor, Guided-Wave Optics (2004-2006).

Honours, Awards, Fellowships, Membership of Professional Societies

IEEE, Senior Member;
Institute of Physics, FInstP, CPhys.;
Czech and Slovak Society for Photonics.

Personal interests

Music; member of an amateur Chamber orchestra "Akademie" (violin).