Nonlinear optics for transducers: principles and materials

H.J.W.M. Hoekstra, G.J.M. Krijnen, A. Driessen,
P.V. Lambeck, and Th.J.A. Popma,
MESA Research Institute, University of Twente
P.O. Box 217, 7500 AE Enschede, The Netherlands

I. Abstract:

This paper concentrates mainly on intensity dependent refractive index changes, due to the third-order optical nonlinearity. Materials exhibiting such effects are good candidates for applications in all-optical devices. The discussion will be on these materials, characterization techniques and an overview will be given of proposed all-optical devices. Of the latter the nonlinear Y-junction will be treated in considerable detail.

II. Introduction.

Since ancient times light has been used as a carrier of information. In technical applications, however, it has played no significant role until recently by the invention of the laser and the introduction of the optical fiber. Nowadays the fiber is widely used in communication networks, allowing for extremely dense information transfer not affected by unwanted perturbations like (other) electro-magnetic radiation.

For the processing of information light has been used since the fifties in analogue or coherent optical computers, utilizing the intrinsic parallelism of light and also that a single lens may perform a Fourier transform of a two-dimensional field pattern. Such coherent optical computers have been used for the processing of information from radar screens, and are still used for process control in factories, e.g. to filter out the smaller details of a product, or to measure the mesh-size of canvas or the thickness of a thin, fast moving thread. Most processing of information today is done by digital electronic computers, which have an impressive, still growing potential.

However, it is expected that the increasing complexity of electronic computers will sooner or later lead to a frustration of this growth, mainly due to the sequential communication in an electronic computer and also by the limited switching time of a transistor and the unwanted interference of signals. To overcome these problems, for some part, (integrated) optics may come into play. The major advantages of applications of optics, for both communication and processing, are the intrinsic parallelism and also the potentially fast switching times (<1ps) of all-optical devices. By choosing the appropriate (i.e. linear) materials, optical signals can propagate close packed (in time or space) without affecting one another. For all-optical processing, however, there is still a need for materials having a strong, third-order nonlinear optical (NLO) effect, with short (~1ps) turn-on and turn-off times.

This paper concentrates mainly on third-order NLO materials. In section III a short introduction will be given into the field of NLO and its applicability. Section IV will be concerned with a short discussion on NLO materials and on a few characterization techniques. In section V an overview will be given of a number of well-known third-order NLO devices. Here the merits of the NLO Y-junction will be discussed in more detail.

III. A short introduction to nonlinear optics

The response of matter to one or more optical or DC fields may macroscopically be described by the polarization, $P(r,t)$. This quantity is in general a

very complicated nonlinear function of the history of the electric and magnetic field distributions. If the effect of magnetic fields may be neglected, and if there is no permanent polarization, the polarization in a uniform medium is given by the following convolution in time and space [1]:

$$P(r,t) = \epsilon_0 \int \chi^{(n)}(r-r_1, \dots, r-r_n, t-t_1, \dots, t-t_n) \cdot \\ \cdot E(r_1, t_1) \dots E(r_n, t_n) dr_1 \dots dr_n dt_1 \dots dt_n. \quad (1)$$

Here $\chi^{(n)}$, the n-th order susceptibility, is a tensor of rank $3n+1$.

It is convenient, for both experimental and theoretical purposes to work with the Fourier transform of the electric fields and the polarization. As (1) contains products of the electric field care should be taken in using the complex notation. The total electric field can be expressed as a sum of plane waves:

$$E(r,t) = \sum E(k,\omega), \text{ with} \\ e(k,\omega) = \{E(k,\omega) + E^*(k,\omega)\}/2, \quad (2)$$

and $E(k,\omega) = E_0(k,\omega) \exp(ik \cdot r - i\omega t)$. Then, considering for the moment only linear polarization, in the presence of a single plane wave, $e(k,\omega)$, it follows from (1-2):

$$P(k,\omega) = \epsilon_0 \int dt_1 dr_1 \chi^{(1)}(r-r_1, t-t_1) \cdot \\ \cdot \{E_0(k,\omega) \exp(ik \cdot r_1 - i\omega t_1) + cc\} \\ = \epsilon_0 \{ \chi^{(1)}(k,\omega) E(k,\omega) + cc \} / 2. \quad (3)$$

In (3) cc stands for the complex conjugate, and

$$\chi^{(1)}(k,\omega) = \int \chi^{(1)}(r,t) \exp(ik \cdot r - i\omega t) dr dt.$$

The higher-order terms, contributing to the polarization, can be obtained in a similar way, i.e. by substitution of (2) into (1) and collecting terms which contribute to the same $P(k,\omega)$ term. E.g. if we consider third-order NLO effects with one incoming beam, $E(k,\omega)$, it follows, by substitution of (2) into (1) that there are two different polarization terms:

$$P(3k, 3\omega) = \epsilon_0 \chi^{(3)}(3k = k+k+k, 3\omega = \omega+\omega+\omega) E^3(k,\omega), \text{ and}$$

$$P(k,\omega) = 3\epsilon_0 \chi^{(3)}(k = k+k-k, \omega = \omega+\omega-\omega) |E(k,\omega)|^2 E(k,\omega) \quad (4)$$

Here we have changed over again to the complex notation, i.e. the true polarizations are given by the real parts of the right hand sides (rhs) of (4). It is of importance to note that the two third-order susceptibilities in (4) arise from different Fourier transforms of the same susceptibility in r,t -space. The degeneracy factors 1 and 3, occurring in (4), are included as is the convention. It is the number of ways in which these products of electric fields can be made, and ensures that the parameters $\chi^{(3)}$ are continuous as a function of the arguments k and ω [2]. E.g. this way

$$\lim_{k_1, \omega_1 \rightarrow -k, -\omega} \chi^{(3)}(k = k+k_1-k_1, \omega = \omega+\omega_1-\omega_1) = \\ \chi^{(3)}(k = k+k-k, \omega = \omega+\omega-\omega). \quad (5)$$

A lot of different nonlinear phenomena are known today, a part of these are given in table I.

The polarization affects the propagation of the light, which may be seen using Maxwell's equations. Depending on the nature of the effect, different approaches may be used. For non-automatically phase-matching effects, such as the SHG, the so-called SVEA (slowly varying envelope approximation) is often used [2]. We will treat here in some more detail the

Table I. Susceptibilities for various NLO effects and its applications. The abbreviations EO, SHG and THG stand for electro-optic, second- and third-harmonic generation, respectively.

SUSCEPTIBILITY	EFFECT	APPLICATION
$\chi^{(2)}(\omega=\omega+0)$	electro-optic (EO) effect	EO modulation of light
$\chi^{(2)}(2\omega=\omega+\omega)$	frequency doubling	SHG
$\chi^{(2)}(\omega_1=\omega_2-\omega_3)$	frequency mixing	down conversion
$\chi^{(3)}(0=0+\omega+\omega)$	quadratic EO effect	EO modulation of light
$\chi^{(3)}(\omega_1=\omega_1+\omega_2-\omega_2)$	Raman effect	all-optical devices
$\chi^{(3)}(\omega=\omega+\omega-\omega)$	AC Kerr effect	all-optical devices
$\chi^{(3)}(2\omega=0+\omega+\omega)$	Electric field induced SHG	SHG
$\chi^{(3)}(3\omega=\omega+\omega+\omega)$	frequency tripling	THG

first- and third-order (intensity dependent refractive index, IDRI) effect. In order to keep things simple we assume an isotropic, current- and charge-free, non-magnetic material. Then Maxwell's equations lead to the following form of the wave equation:

$$-\Delta E(\mathbf{k}, \omega) + \frac{1}{c^2} \frac{\partial^2 E(\mathbf{k}, \omega)}{\partial t^2} = -\mu_0 \frac{\partial^2 \mathbf{P}(\mathbf{k}, \omega)}{\partial t^2} \quad (6)$$

The solutions of (6) are plane waves of the form:

$$E_1(\mathbf{k}, \omega) = E_{a1}(\mathbf{k}, \omega) \exp\{i(\mathbf{n}\mathbf{k}_0 \cdot \mathbf{r} - \omega t)\},$$

$$\text{with } |\mathbf{k}_0| = \omega/c, \text{ and } n^2 = 1 + \chi^{(1)} + 3\chi_{111}^{(3)} |E_1(\mathbf{k}, \omega)|^2 \quad (7)$$

Eq. (7) is the expression for the ideal Kerr-law nonlinearity, neglecting higher order effects leading to e.g. saturation of the NLO effect. A notation often encountered in the literature is:

$$n = n_0 + n_{2E} |E|^2 = n_0 + n_{2S} S, \text{ with } n_{2E} \approx 3\chi_{111}^{(3)} / (2n_0). \quad (8)$$

Here S is the energy flow (in W/m^2) of the beam and from standard theory it follows that:

$$n_{2S} = \frac{2}{n_0 \epsilon_0 c} n_{2E}. \quad (9)$$

Inspecting eqs.(1-5) it follows that, if the susceptibilities $\chi^{(i)}(\mathbf{r}-\mathbf{r}_{i-1})$ are vanishing unless $|\mathbf{r}-\mathbf{r}_i| < \lambda$, with $i=1, \dots, n$ and λ is the wavelength of the light, the Fourier transforms are approximately $\mathbf{k}$ -independent. This situation may be met if the NLO material consists of relatively small, non-interacting molecules, but for example not in semi-conductors if mobile charge carriers or excitons are involved. Such nonlocal effects generally hamper the solution of the Maxwell equations in e.g. the presence of optical waveguides and may also affect device performance [3]. If the above approximation holds, which is often assumed in simulations, the argument $\mathbf{k}$ in (7) may be omitted, thus facilitating it to solve the wave equation for a propagating electric field pattern, generally consisting of a summation over plane waves. The latter holds for non-uniform media, e.g. media in the presence of waveguides.

IV. Third-order NLO materials

Theory

Third-order NLO effects give rise to a lot of interesting phenomena as depicted in table I. For applications in all-optical processing at a single frequency the optical Kerr-effect (or IDRI) is of special importance. This section concentrates mainly on this effect, although part of the discussion holds equally well for related effects as Raman-active nonlinearities or the third order electro-optic effect.

To start the discussion on the IDRI we believe

that it is instructive to consider a three-level molecule. Fig. 1 shows an diagram of a molecule having three electronic levels [4]. If the molecule gets excited by incident light the state S_1 gets populated at the expense of the ground state. It is of importance, in order to understand the underlying mechanism of the IDRI, to note that, by the population of S_1 , the absorption (and therefore the refractive index) of the molecule will change *only* if the transitions S_1-S_2 differ from that of the ground state, i.e. if state S_1 has a *different*

Fig. 1. Schematic of the electronic energy levels of a saturable absorber.

polarizability, compared with the ground state. Above we have in fact discussed the resonant case. Similar conclusions hold for the non-resonant case, where the excitations do not occur, but where the excited states are mixed into the ground state by the optical field.

One of the earliest attempts to find analytical expressions for the third-order susceptibility of polymers uses a model in which $2M$ electrons are confined to a one-dimensional box of length $2L$, oriented along the z -axis. [5]. Using perturbation theory the result is, for large L :

$$\gamma_{\text{max}} = \frac{256L^{10}}{45a_0^3 e^2 \pi^6 M^5} \quad (10)$$

Here a_0 is the Bohr radius, and γ is the second hyperpolarizability. The result has been obtained by taking the fourth derivate of the ground state energy with respect to the electric DC field. So, the result should correspond to the non-resonant value and

predicts the right order of magnitude for polyenes and cyanines [5]. Assuming $M \propto L$ it follows that $\gamma \propto L^5$. In (10) the strong dependence of γ on the chain length can be attributed both to an increasing dipole strength and an increasing energy gap as a function of the chain length, L .

For long polymeric chains the box-model, described above, predicts non-transparency, which can indeed be observed for some classes of polymers, such as cyanines. Polyenes, however remain transparent even for very long chain lengths due to a Peierls transition [6]. In the theoretical model used by [5] this has been accounted for by using a sinusoidal potential, leading to a non-vanishing band gap, E_g . Using an extension of this model Sauteret *et al.* [7] found the following relation for infinite polymeric chains of polyenes:

$$\chi_{zzz}^{(3)} = \frac{2^5}{45} \pi^2 \frac{e^{10}}{\sigma} \left(\frac{a_0}{d}\right)^3 \left(\frac{1}{E_g}\right)^6 \quad (11)$$

As far as we know the only calculations giving analytic expressions of the third-order susceptibility as a function of photon energy, ω , have been published by [6]. These authors use the Keldysh non-equilibrium Green's function method, with the band gap as the only adjustable parameter. Their results are in excellent agreement with measurements of the THG as a function of ω in trans-polyacetylene, and predict the correct order of magnitude for the IDRI. Detailed measurements of the latter for comparison with the calculations are not available at the moment. From the analytical expressions, given by [6], we deduce a dependence $\chi^{(3)} \propto 1/E_g^6$ for the DC limit, in agreement with the result of [7].

Various different *ab initio* methods are used to day to calculate non-linear susceptibilities, we will discuss shortly two of the most frequently used. (i) The hyperpolarizability is obtained from the differential of the ground state energy with respect to a static electric field [8]. Here two approaches

Results obtained with the first method, (i), [8] on trans-polyacetylenes, $C_{2p}H_{2p+2}$, $p=1.5$, show a power law dependence: $\gamma \propto L^5$, for $p=2$, in remarkably good agreement with (14), obtained in a relatively simple way. A similar power dependence has been found by [10] for $\gamma(3\omega=\omega+\omega+\omega)$ of trans- and cis polyacetylene at $\omega=0.65\text{eV}$: $\gamma \propto L^{4.7}$.

Materials

Today, a lot of materials, showing more or less strong NLO third-order effects are known. The characteristics of some of these materials are depicted in table II. Below we will discuss the most promising, with respect to applications in fast, all-optical devices, materials: MQWS (multiple quantum well structures) [11], embedded noble metal and semi-conductor (CdS_xSe_{1-x}) particles of nanometer size and polymers.

QWS consist of ultra thin, typically 100Å, layers of semiconductor materials having physical compatibility but a different composition. Thus the band gap may be modulated in a direction perpendicular to the layers, leading, for a sufficient large modulation, to a confinement of the carriers. So, the band-structure is 2D in nature.

As in 3D semiconductors, Coulomb attraction leads to bound electron-hole (e-h) states or excitons. The effect of the confinement leads to an artificial decrease of the e-h distance, and thus to an increase of the binding energy of the excitons, and also to an enhancement of the exciton density of states. The latter leads again to an increase of the oscillator strength for excitations to exciton states.

This large binding energy leads to more stable exciton states, which has a drastic effect on the complex refractive index due to both phase-space filling and screening effects. The third-order NLO effects in MQWS of GaAs/AlGaAs are extremely large (see table II). In this material the lifetime of

Table II. Experimental values of n_2 at room temperature, the corresponding reaction time and the saturation value of the refractive index change (if known), Δn_{sat} . The wavelength, λ , is given only if there is a unique wavelength(-region) for the IDRI. The used abbreviations are: o=orientational, t=thermal, e=electronic and ph=phase-space filling.

Material	$n_2(\text{m/V})^2$	τ/sec	Δn_{sat}	$\lambda/\mu\text{m}$	effect	ref.
MBBA(liq.cr.)	10^{-12}	10^{-6}	0.1	-	o/t	[12]
ZnS	10^{-13}	10^{-6}	-	-	t	[12]
CdS_xSe_{1-x}	$2 \cdot 10^{-17}$	10^{-6}	-	-	t	[13]
doped glass }	$-4 \cdot 10^{-18}$	10^{-10}	0.001	-	e	[13]
polydiacetylene	10^{-18}	10^{-12}	-	-	e/ph	[14]
polythiophene	10^{-17}	$< 10^{-12}$	-	-	e	[15]
GaAs/AlGaAs (MQWS)	10^{-9}	$10^{-12} - 10^{-9}$	-	0.84	e/ph	[11]
Embedded nanop. of noble metals	10^{-16}	$< 10^{-12}$	-	plasmon resonance	e/th	[16]

can be followed here, in the first the self-consistent field (SCF) equation is solved in the presence of a finite field, and α and γ are obtained by finite differencing. In the second the differentiation is performed analytically, this involves solutions of coupled perturbed Hartree-Fock solutions [9]. (ii) The hyperpolarizability is calculated using the so-called direct summation method [10]. Here the matrix elements for dipole transitions and the energies of excited states are computed by some SCF method, by substituting these quantities into analytical expressions for the susceptibilities (the electronic contributions to) the latter are obtained.

excitons is about 1ps, experiments [11] have shown that after a strong excitation pulse, having a photon energy equal to that of the exciton transition, the absorption coefficient (at that photon energy) drops within 1ps and recovers slowly. The relatively long recovery time (1ns) is due to interactions with free e-h pairs, and is quite disadvantageous for applications.

Recent experiments on small structures in MQWS indicate that the slow recovery times can be overcome by diffusion of the free e-h to the surface followed by recombination [17].

Quite interesting, and much promising for

applications in all-optical logic and memory devices, is the behaviour of MQWS of GaAs/AlGaAs in the presence of an electric field perpendicular to the layers [11]. Then, the exciton wave functions change quite drastically, leading to a change of the optical properties, such as a shift of the exciton peak. This effect is often referred to as the quantum confined Stark effect, and is used in so-called SEED's (self electro-optic devices). The latter are used today in laboratory experiments on optical computers as logic and memory devices, operating at low switching energies [18].

In small (1-10nm) noble-metal particles suspensions the NLO effects are attributed to the quantum size effect (QSE), i.e. to the confinement of the electrons, although thermal effects cannot be ruled out [19]. Usually, thermal effects lead to large reaction times, but for such small particles the heat diffusion is a fast (≈ 1 ps) effect.

As mentioned above, the QSE leads to a large increase of the third order NLO effects for small metal particles. An extra enhancement can be obtained if small noble metal particles are used, at frequencies of the light close to the plasmon frequency. This may be explained as follows. For small (size $\ll$ wavelength) particles the electrostatic approximation may be used. The relation between the electric field of the radiation in a particle, E_p , and that of the incoming field, E_m , is then given by [20]:

$$E_p = \frac{3\epsilon_m}{\epsilon_p + 2\epsilon_m} E_m \quad (12)$$

Here ϵ_m and ϵ_p are the dielectric constant of the host medium and the metal particles, respectively. For noble metals the real part of ϵ_p is negative, for frequencies below the plasmon frequency, so that, for a suitably chosen host and frequency, we may find:

$$\text{Re}(\epsilon_p + 2\epsilon_m) = 0. \quad (13)$$

This is the condition for plasmon resonance. If eq. 13 holds this will lead to a strong enhancement, of orders of magnitude, of the electric field inside, and in the vicinity of, the noble metal particles, and therefore to a strong increase of the third order NLO effects [19,20]. It has been shown [20] that using the expression for the IDRI (see section III), (12) may have more than one solution for E_p , at a given E_m , leading to an intrinsic optical bistability, thus allowing for memory devices on a sub-micron scale.

The above discussion holds as well for noble metal particles embedded in a NLO host, but here the conditions may be chosen such that a much, more stronger enhancement of the NLO effects are obtained. For pure thermo-optic materials, such as ZnS(e), the third order ONL effects are large but slow on a picosecond time scale. We remark that, using such a material as a host for small noble metal particles, advantage may be taken from both the plasmon enhancement effect in the vicinity of the metal particles, and the fact that heat will diffuse away from such a small particle within a few picoseconds. This way strong ONL, fast reacting materials can be obtained, suitable for applications in the field of optical phase conjugation, opto-optic devices and small sized memory elements, working at relatively low intensities of the light.

Other suggestions in this field have been presented by [21] and consist of nanoparticles, having a ONL core of e.g. polymers. Their calculations show that the presence of such a core leads to an increase of the nonlinearity and to a lower onset of optical bistability.

With respect to second-order ONL effects, organics can compete with anorganic crystals. Inspecting table II it follows that a similar remark cannot be made with respect to the IDRI, the value of n_2 in polymers is not better than $10 \cdot 10^{-17} \text{m}^2/\text{V}^2$. For

practical applications in all-optical devices this value is far too low and MQWS seem to be favourable here, at least at the moment.

The advantages of polymers are that these materials have fast response times and can be tailored to have (i) good transmission properties in the desired optical frequency range and (ii) higher values of n_2 . With respect to the latter there is a need for systematic, both experimental and theoretical, investigation to which organic group or combination of groups may lead to an enhancement of the effect, and also to the influence of the chain length.

Characterization

In order to utilize ONL effects in optical devices and also for material characterization it is advantageous to use optical waveguides as (i) this leads to a strong confinement of the optical field, and (ii) the propagations of modes is diffractionless, leading to long interaction lengths. Accurate measurements of NLO effects are of importance both for device modelling and in order to get insight into the material properties. Many different characterization methods, mostly based on interferometric effects, may be used to measure the reaction time and magnitude of third-order NLO effects, see [22]. In this section we will discuss some methods based on prism coupling into planar structures for the determination of the magnitude of the IDRI and also of the second- and third order electro-optic effect.

Choosing a coordinate system as given in figure 2, the differential equation for the coupling of both the signal and the pump beam is given by [23]:

$$\frac{dA_m}{dz} = -(K_m k_0 + \beta_{m,i}) A_m + t_m K_m k_0 E_0 \exp(i\Delta\beta \cdot z) \quad (14)$$

Here E_0 is the amplitude of the electrical component of the incoming beam at the prism base, A_m is the amplitude of the modal field which is related to the electric modal field, E_m , by

$$E_m(x,z) = A_m(z) \xi_m(x) \exp\{-i\beta_{m,z} z\}. \quad (15)$$

$\Delta\beta_r = k_0 n_p \sin(\theta) - \beta_{m,r}$, where k_0 is the wavevector, n_p is the refractive index of the prism, and θ is the angle of incidence on the prism base. $\beta_m = \beta_{m,r} + i\beta_{m,i}$ is the propagation constant of the mode. In (15) the field shape ξ is defined such that $|A_m|^2$ represents the power of the mode per unit length in the y-direction. The coupling constants K_m and t_m are interrelated [24] and may be obtained, for a given structure, in a way described by Tien and Ulrich [25] or by [26].

In the presence of a third-order nonlinearity the propagation of the mode becomes power dependent and, neglecting any power-dependent changes of the modal field it follows [27]:

$$\beta_m(z) = \beta_m^0 + \beta_2 |A(z)|^2. \quad (16)$$

The relation between β_2 and the material parameters can be determined using standard perturbation theory [28].

With the above it follows that, for prism coupling with a single beam, the coupling efficiency is power-dependent. This way the NLO properties of the involved materials can be measured [29].

In the presence of a modulation of the signal beam by a stronger beam, either at a different wavelength or exciting a different mode, coherent detection techniques can be used [13,26,30], see fig. 2. Such a set-up leads to a very sensitive detection of changes in the refractive index, $\Delta n \approx 10^{-8}$, allowing also for the measurements of saturation effects, Raman processes ($\chi^{(3)}(\omega = \omega + \omega_1 - \omega_1)$), non-ideal Kerr-law behaviour and the performance of time-resolved pump-probe processes. Angle dependent measurements of the out-coupled power at the output prism of the signal beam and of its modulation by the pump beam are shown

Fig. 2. Experimental set-up for the coherent detection of modulation of a the coupling efficiency of the signal beam (HeNe) by a pump beam (Ar⁺). The abbreviations are AOM= acousto-optic modulator, and PD=photo-detector.

in figure 3. The coupling angle of the pump beam remains unchanged. Changes in both the real and imaginary part of the refractive index can be revealed[26] (see also [14]).

A similar modulation technique may also be used to determine both the second- and third-order EO coefficient, see [31,32], who used an ATR configuration for their experiments.

Fig. 3. Experimental results obtained with the equipment depicted in fig. 2 [26].

V. All-optical devices

A large variety of integrated optics devices, utilizing the IDRI, have been proposed and partly realized and tested the last fifteen years. The effects, on which the performance of these devices rest, may roughly be subdivided in:

i. a change in the modal propagation constant ($\Delta\beta$), leading to a phase shift ($\Delta\phi$), made effective by interference with some other beam or mode, occurring for example in Mach-Zehnder interferometers (MZI) and distributed (prism or grating) couplers,

ii.a $\Delta\beta$ (and $\Delta\phi$) for a device with a performance depending critically on some dimension of the device such as in a Fabry-Perot (FP) etalon or a grating mode-converter,

iii. a change in the refractive index, having the order of magnitude of the linear index differences in the device, such as occurring in the case of spatial soliton emission, NLO Y- and X-junctions and optical limiters.

iv. devices utilizing, besides the effect mentioned at ii, the intensity dependent cross-phase modulation between different modi, e.g. logic switches,

v. optically bistable (OB) elements such as FP etalons, gratings and distributed couplers, OB is caused by some feedback mechanism,

vi. hybrid devices working not solely in the optical domain SEED's.

In table III we have given a survey of a number of more or less well-known third-order nonlinear devices, for completeness also SEED's are mentioned, although their performance is based on higher-order NLO effects.

For detailed discussions on the devices given in table III the interested reader is referred to the indicated papers. Here we will treat in some more detail the merits of devices consisting of a single (non)linear asymmetrical Y-junction. A clear understanding of such a device might be of help in interpreting the performance of devices consisting of a combination of Y-junctions, such as the X-junction or the MZI.

Y-junctions are of interest in Integrated Optics due to the versatility of the functions that can be performed with these structures and the relaxed fabrication tolerances (as compared to directional couplers for example). Burns & Milton [33] have shown that Y-junctions can act either as power-splitters or mode-splitters. Then, from reciprocity, it can be understood that Y-junctions can also be used as mode-converters and signal-combiners provided that the conversion to radiation modes in the Y-junction structure is negligible. The requirement for this is that the crossing angle is sufficiently small, so that the modal field propagation is adiabatic. In order to perform BPM (beam propagation method, [39]) simulations, it is convenient to approximate the 3D

Fig. 4. Schematic of the considered Y-junction.

structure by a 2D-one on using the effective index method (EIM, [28]).

In fig. 4 a 2D picture is given of an asymmetric Y-junction. In [33] it was shown that asymmetric Y-junctions consisting of one bimodal input and two nonidentical mono-mode output channels can act as mode

Table III. An overview of third-order nonlinear devices, indicating whether a given performance has been reported or may be expected (y) or not (n), and the corresponding references.

	performance						references
	switch	memory	logic switch	limiter	isolator	amplifier	
Y-junction	y	y	y	n	y	y	[33,34]
X-junction	y	y	y	n	y	y	[3,35]
hollow WG	y	n	y	n	n	y	[36]
directional coupler	y	n	y	n	n	y	[3,22]
FP etalon	y	y	y	n	y	y	[37]
mode-converting grating.	y	y	y	y	n	y	[3,38]
spatial soliton device	y	n	n	y	n	y	[22]
MZI	y	n	y	n	n	y	[22]
distributed coupler	y	y	n	n	n	n	[22]
WG, $n_2 < 0$	n	n	n	y	n	n	[22]
4-wave mixing dev.	n	n	n	n	n	y	[22]
SEED's	y	y	y	n	n	n	[11]

splitters. As a key parameter a Mode Conversion Factor (MCF) can be defined by:

$$\text{MCF} = \frac{N_2 - N_1}{2\theta (N^2 - n_3^2)^{1/2}} \quad (17)$$

where θ is the half branching angle, n_3 is the index of refraction of the medium between the two branching angles, $N = 0.5(N_1 + N_2)$ and N_1 and N_2 are the effective indices of waveguides 1 and 2 at infinite separation. For $|\text{MCF}| > 0.44$ it was found that the Y-junctions act as mode-splitters enabling efficient power transfer from the input channel to mainly one of the output channels whereas $|\text{MCF}| < 0.44$ leads merely to a division of power over both output channels.

From reciprocity it can be understood that an Y-junction with large MCF and low conversion to radiation modes can also be operated in the opposite direction i.e. light launched in one of the two inputs is efficiently coupled to the fundamental or first order mode of the output channel.

It is clear from (17) that the MCF and thus the behaviour of the Y-junction is power-dependent in the NLO case. This can also be seen from the results of the BPM simulations depicted in fig. 5. Using the parameters of table IV and an over-all nonlinearity of $n_2 = 10^{-13} \text{m}^2/\text{V}^2$, and effective indices of $n_0 = 1.59$ and $n_1 = 1.6$ for the background and the waveguiding sections, respectively. The wavelength is $1 \mu\text{m}$, and the fundamental mode is launched into the lower branch at the lhs of fig.4. From fig.5 it follows that at low power levels the field is converted into a first-order mode, whereas at higher power levels the output is mainly the fundamental mode. Placing another Y-junction, but now a linear one, somewhere further on in the structure the device acts as an all-optical switch. Thus, the combined Y-junctions resemble the X-switch [35]. The device is non-reciprocal as a fundamental mode, launched at the rhs of the junction (see fig.4) will leave it mainly, more than 99.9% for not to high power levels [40], through the upper part. So, it can be used as an optical isolator of a pulsed

laser, at least if things can be arranged such that a reflected pulse cannot coincide with a new incoming pulse in the effective part of the junction.

We also expect that the device may be used as an all-optical amplifier and a logic gate. Similar interesting features have also been described by [35] for a X-junction.

The switching curve of fig. 5 becomes much steeper if, similar to the idea of [36], one of the two branches is a hollow waveguide. In fig. 6, results are shown for a Y-junction where one of the branches is the only nonlinear part of the structure, which

Fig. 5. Switching behaviour of the y-junction depicted in fig. 4. The parameters, used for the simulations, are: background index $n_0 = 1.59$, waveguide index $n_1 = 1.6$, homogeneous nonlinearity $n_2 = 10^{-13} \text{m}^2/\text{V}^2$ and $\lambda = 1 \mu\text{m}$. For the widths we have used $w_1 = 2.25 \mu\text{m}$ (case A and B) and $2.5 \mu\text{m}$ (case C), and $w_2 = 2 \mu\text{m}$. The crossing angle was $2\theta = 0.2035^\circ$ (A and C) and 0.4035° (case B).

has, in the active region of the junction a linear refractive index equal to that of the background. The fundamental mode is launched into the rhs (see fig. 4), and above a certain threshold soliton emission occurs into the hollow branch. The latter corresponds to the TE1 mode, see fig. 6.

Fig. 6. Switching behaviour of a Y-junction having one branch consisting of a hollow waveguide, also being the only NLO part of the structure. Here a fundamental mode is launched at the rhs (see fig. 4), and the power in the TE1 mode represents the power leaving the junction through the hollow branch. The parameters are similar to the ones given in the caption of fig. 5, except $n_g = 1.595$ and $2\theta = 0.1^\circ$.

VI. Concluding remarks

The past years a large variety of all-optical devices have been proposed, a part of these has been realized and tested. To increase applications of such devices there is still a need for strongly nonlinear, fast reacting and (possibly) non-absorbing materials. In this field further research, both experimentally and theoretically is desirable in order to obtain more insight into the underlying mechanisms and might be of help for the tailoring of materials.

Simulations of all-optical devices mostly assume an ideal Kerr-law nonlinearity and a cw input. However, the response of a device to fast pulses might differ considerably from the predictions obtained by simulations, and pulse break-up may occur. The latter effect may possibly be overcome by using temporal solitons [3]. Further simulations are needed, using realistic material parameters, in order to realize devices with good performance.

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