A SHORT BIBLIOGRAPHY

OPTICAL PULSE COMPRESSION
BY SOLITONIC EFFECTS
IN SILICON PHOTONICS

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0.1 SILICON PHOTONICS AND COMPETITORS, PERSPECTIVES AND STUDIES

0.1.1 Applications and Context of the research

The photonics contribution to overcome the current limits of fast electronics is guessed to become a major technological breakthrough. Indeed, the best pcb electronic circuits hardly go beyond the GHz range, viz 100GHz waited for optical circuits. Sub nanosecond signals from classic transistors are now standard, but they lie far above picosecond -even hundred of femtosecond- wave forms that photonics sources may deliver.

Furthermore, a real revolution will be to replace all the numerical/non linear functions today assumed by transistors/integrated circuits and electrical interconnects, by all optical sources, wave guides and signal treatment. That argument is particularly striking as photonic integration could be compatible with today electrical Cmos process. It is anticipated since 2018 era, under the pressure of Data centers, that a crossing may occur between electrical and silicon photonic interconnects, due to lowered costs [28].

A simple glance on actuality, [20] shows some additional trends for 2023/2028 era :

1. except the absolute $ market amounts, the TCAC (annual averaged yield insuring the investments) is evaluated to around 25% (24.98),
2. The Asia/Australia continents are deeply involved in R&D, with lower effort in Europe/American one,
3. Not only the hardware side of the market (speed) is to be central : indeed, the neural networks claim to replace the high density brute force GPU circuit, not only by cycle/s, but also with innovative AI softwares ; appliances, (listed here without any ethic nor exhaustive consideration . . .) will include bio informatics, medicine design, Artificial Intelligence, the Games (metavers...) and fabrication processes,
4. Data centers as we mentioned, will be the engine for the market, followed by streaming video and multimedia and telecommunications

To add, the solar power domain, having probably a weight not enough evaluated.

A first market review, as crude as that one, should be somewhat sparse, if we didn't look around concurrent technologies. Let's have a glimpse to Bio photonics, which is for instance, a candidate for micro sensors. Market proportion, cost, mutual perveance between the two, is an interesting direction to dig.

0.2 STATE ON THE ART WITH Si/SiO2 WAVE GUIDES

0.2.1 Qualitatively

Schematically, solitonic propagation inside solid states wave guides necessitates a photonic (laser) coupling, the material response, and the features of plane circuitry. The entire mechanism is well reported by Agrawal and Al, with a physics point of view [17]. To summerize that reference :

Photonics on Si/SiO2 did represent during years, an excellent playing field ; transparent beyond $1.1\mu m$, centrosymetric, it offers with its associated oxide, an high index contrast $n_{Si} = 3.5$˘$n_{SiO2} = 1.5$, favoring optical modes confinement and third order - and even higher- non linearity [3]. It is compatible with standard CMoS fabrications for high integrated electronics -for instance SOI processes, a French successful innovation by Soitec- and is a low cost material. However :

1. The Kerr coefficient of active silica wave guide (SiO2) is considered as 100 times lower than for its Silicon support, and is of approx 5.18 nm^2W^{-1} [25] ; that features enables, depending of applications, playing or not with Si non linearities. It is to be noted that for fiber optics domain, the propagation medium IS Silicon. So Kerr is a favored factor in that case.

2. In the same way of thinking, Raman effect, when it manifests by positive interaction of photons with crystal phonons, could be a gain factor for non linearity/compression. But phonons have the bad taste to interact also negatively, inducing losses. The balance is contributing correctly only with special arrangements like SRS (Stimulated Raman Scattering) which are yet exploratory ; Raman scattering is generally linked to the -Raman part of- the third **Photonics** susceptibility coefficient χ of the Silicon, and typically associated with an optical phonon lifetime of approx 3ps, then a « narrow band » spectrum. Later, that branch may degenerate to other optical phonons, and finally to acoustical one (thermal and vibronic effects inside the crystal). Only the first interaction may have an importance inside our scope. Direct interaction with longitudinal phonons - Brillouin scattering- is considered as minor also in that case,

3. Si has a low gap Valence/Conduction of 1.12eV, so a part of photon population will create electron-hole pairs, via Two Photon Absorption (TPA). These pairs subtract to the communication balance and power yield, they don't contribute to propagation, but to diverse phenomena like Auger non radiative transitions, phonon negative exchanges, sometime exitonic behaviour and thermal state crystal levering. These supplementary parasistics grow due to indirect gap character of Si. Momentum conservation needs an additive adaptation to match in the Brillouin zone, and it is carried by phonons.

4. Another parasitic effect of the Si low gap, is the Free Carrier Absorption (FCA). It manifests by the photon interplay with conduction/valence bands ; photons are the driving forces to electron-holes creation and dynamics, via semiconductor -diffusion-equations. FCA is in majority present by a non linear effect on index, via the n_2 change, ie optical Kerr effect [11], [10]. It is found that beyond high levels of doping, FCA manifests also by a dispersion law modification. However, the -conduction band carrier- levels of reflectivity minima for III-V family are doping sensitive above $10^{18} cm^{-3}$, and lie in mid infrared. And regarding hole susceptibility, results are yet parses.

Then, by that short part, are summarized advantages and drawbacks of the couple Si/SiO2. Of course, some other couples offer splendid performances. On other hand, they are sometime costly, toxic, and/or of difficult integration.

0.2.2 a Si/Sio2 Physics parenthesis

[17] depicts clearly the characteristic times and characteristic lengths of the main phenomena. It helps to apprehend the relative balance of the diverse behaviours. Firstly, the coupled signal experiences a distortion inside the wave guide (generally spreading in the case of natural dispersion, of the wave colored components, so called Group Velocity Dispersion GVD). GVD comes from material index variation, but also from the chosen wave guide geometry.

By contrast with Silicon, which appears dispersively stable, in some electromagnetic mode configuration, GVD becomes anomalous **for SiO2** beyond 1.27 μm, ie UV waves acquires higher speed inside the wave packet, rendering it asymmetric. That side, somewhat sneakily technical, illustrates only the fact that spectral engineering of a soliton candidate, must takes account the distortion.

The characteristic dispersion length is given by, $l_{dispersion} = \frac{T_0}{|\beta_2|} \sim 50cm$, ie a very large length is meaning a low variation of dispersion for short (ps) laser pulses.

Going to the non linear part, a relation links real and imaginary parts of the -Electronic part of - the third **Photonics** susceptibility coefficient χ_e^3 of the Silicon by :

$$\frac{\omega}{c} n_2(\omega) + \frac{i}{2} \beta_T(\omega) = \frac{3\omega}{4\epsilon_0 c^2 n_0^2(\omega)} \chi_e^3 \tag{1}$$

where χ_e^3, is better described inside the reference, and is of tensorial nature.

Here, we observe the competition between Kerr optical effect n_2 and the Two Photon Absorption coefficient β_T. The relative weight of Kerr effect is low before TPA, around $1\mu m$ (of course because of high TPA around 1.1eV), but raises progressively, following the Non linear Factor of Merit $NFOM = \frac{n_2}{\lambda \beta_T}$ until $2\mu m$ (beyond $2\mu m$, Silicon is quasi free of TPA). These two effects are extremely shorts, ie somewhat 10fs. In fact, they are the initiating sources of slower ns range parasitics, ie Free Carrier Absorption and Free

Carrier Index change (FCI).

Free carrier effects, in majority FCA, then driven by **ultrashort optical Kerr**, are sustained by the pulse repetition frequency prf. Indeed, the charge generation needs a refreshment to be extinguished (electron-hole recombination, damping of carrier layer) before next pulse. How is it described ? We have now to work with **induced polarisability coefficient**, ie a non linear susceptibility coefficient, but linked to the carriers dynamics, not exclusively to the photon-Si interaction, which slightly complicates the scenario[1].

More precisely, with Drude model frame, one defines a new Multipole polarisability temporal tensor, $P_i f(r,t)$, linked with the binormal -in other term used in plasma, bipolar-carrier density. Playing with time-frequency transform, a complex susceptibility response is then defined by :

$$\chi^f(\omega) = 2n_0[n^f + \frac{ic\alpha^f}{2\omega}] \tag{2}$$

Where -probably- the Kramer Kronig relations and/or the diffusion carrier equations allow us to define its real part n^f, or Free Carrier Index, and imaginary one α^f, or Free Carrier Absorption FCA, as functions of the carrier Nn, Nh densities.

In many practical configurations in Si/SiO2, FCA is of 10^4 high order than FCI.

These two parameters are static. We have now to free the propagation « film », it is the scope of the non linear Maxwell/Helmholtz equation. That equation resumes the semiconductor diffusion equation and the photonics, because, during the propagation, the interactions times are no longer negligible. So we integrate again some Raman terms, but prior conclusions about it remain unchanged, if the signal is out of Raman spectrum (105 GHz).

The additional features carried by propagation equation, is the evolution of the wave packet, where the propagation exponent is no more simple, but multi varied (spectral). Furthermore, there is also a nonlinear component inside it, which is yet proportional to the third susceptibility coefficient, then we meet again the non linear Kerr parameter, and TPA coefficient by :

$$\chi^e = \frac{\omega_0}{ca}n_2 + \frac{i}{2}\frac{\beta_T}{a} \tag{3}$$

where a is the « effective mode area », computed by the ratio of confined power of a wave guide section to the total power flux.

A new quantity is now defined, $L_N = [\gamma_0 P_0]^{-1}$ which quantifies the non linear coupling, and its role on Self Phase Modulation (SPM). L_N may reach some mm or less, with moderate peak powers, so immediately, SPM manifests itself.

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[1] FCx could also be generated by the classical Electric Displacement, via first order χ^1[16]

The configuration of electromagnetic modes of propagation is determinant, as explained now. The power is essentially carried by transverse components of the fields ; whether the modal population is TE or TM, Raman effects, for instance, may be low or not. Establishing the frequency non linear equation of propagation, a key parameter of mode influence on non linearity is given -in the general case- by $\gamma_{ijkl} = \frac{3\omega_i \eta_{ijkl}}{4\epsilon_0 c^2 a_{ijkl}(n_i n_j n_k n_l)^{\frac{1}{2}}}\chi^3$ where η is the « mode overlap factor », and a is the effective mode area defined above.

These integrals on the fields, around geometric sections, illustrate the field confinement brought by the mode configuration. By analogy with optical fibers, a strong index contrast between the wave guide and its surrounding material favors mode confinement (a in denominator, is low), so the non linearity coefficient γ raises.

The Kerr non linearity may vary according to the choice of the mode but also to injection polarisation. Practically, we hope to neglect Raman (out of spectrum) and for moderate pulse energy ($<$ 125pJ with a section $0.5\mu^2$), FCA is considered minor for ultrashort pulses (with low prf(s)), relatively to carrier life time ($\sim 100ns$), and TPA dominates. The carrier behaviour is adiabatic, so they oscillate with the propagation wavelength. Knowing γ_{ijkl} we are then able to calculate the Kerr coefficient n_2

Furthermore, amplitudes losses are to consider, but phases are also predominant, so the precedent coefficient must be analysed about their role on Phase shifts, or equivalently, on displacement of spectral components inside wave packet, and pulse chirp. One can show that for pulses of 20pJ or higher, The free Carrier Effects becomes predominant, resulting in a global Blue shift of the wave during propagation, so a spectral peak of a Gaussian pulse, for instance, puzzles into several peaks, one of them lying under the initial range, by a fraction of μm.

Inside a Si/SiO2 couple, a wave packet may see a compression, because **locally**, the GVD due to material is too week to compensate either Kerr more generally, Self Phase Modulation. But properly engineered by Wave guide dispersion for example, these different corrections on the Phase may compensate, on an entire path, ie in average. The central expression is then

$$\gamma_0 P_0 L_d = 1 \tag{4}$$

As Gaussian shape is not a natural solution of soliton regime, the packet is considered to evolve to sech wave shape, so mathematically, a compression in spectral and temporal domains occurs, but in a specific interval. Just let the propagation path be longer, and the wave shape unfold itself.

0.2.3 Theoretical point of view

That approach is not conceptually different, and is well described by [18], and devoted to description of wave packet behavior in weakly non linear media. An example is the transmission electromagnetic line, where one replaces linear condensers by non linear one, or with the magnetic switch technology in electrical engineering.

The formalism of Non Linear Schrödinger Equation, NLSE, mainly consists to add to the standard equation, which describes the linear propagation immersed in a potential, in semi classical description (Electric field is understood to be the average observable of some wave function), an ad hoc combination of linear and power terms of that wave function, including derivatives.

There are constraints, the order of the terms stops at Φ and $\frac{\partial}{\Phi}$ (weak non linearity). [2] A simplified formulation is :

$$[i\frac{\partial}{t} - P(\frac{\partial}{x})^2 - Q|\Phi|^2]\Phi = 0 \tag{5}$$

Plane waves -useful tool however to Fourier decomposition of a solution- should not be themselves stable solutions, according to sensibility of some states to even small perturbations [3].

If we admit locality[4], in short the solution space should be topologically close, or be included inside an homotopy class[21]- it is generally assumed an envelope wave shape of soliton, forced solution in sech (1/ch) where amplitude is linear in (x,t) but phase presents non linearities.

A positive aspect of theoretical side is to ask questions, even if they may appear out of context :

1. the pictorial land of NLSE inside fibers optic is « an isotropic, lossless, non amplifying polarization preserving single mode… », which does not apply to specific cases of 1D,2D wave guides in SOI,
2. locality is to be interrogated systematically ; free carriers are generators of non locality,
3. the intensity dependence of group velocity is to consider ; it drives to a term like $\partial_x[|\Psi|^2\Psi]$,

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[2] Another surprising constraint is the invariance of the solution under Galilean transformation. In the case of Photonics, we should better speak of Lorentz transform ?

[3] hence the term of « Modulation Instability », invoked to explain such complex regimes

[4] locality is not considered as a subject in our scope, except for specific domains as birefringence, so crystal orientation in case on non amorphous materials may be important. Also the in homogeneous impedance wave guides ask for that, because of variation of propagation parameters in the path

4. formalism depends of the temperature ; at extremely low temps, ie for quantum applications of Si Photonics, crystal potentials, Wannier exitons, must be integrated to picture, Phonon resonances and corresponding life times are different,. . . ,
5. there seems to be a correspondence between the three-body interaction at low temperature, and the perturbations induced by in band traps like semiconductors nanocrystals (super lattices of hundred of atoms, hosted by the Si matrix) ; so it is waited to meet some non conventional solitons (dark, dark-bright,dark-bright-bright-bright and so on !) in favored configurations,

It would be vain to imagine resuming Today theoretical efforts.

However in a few words, the possibility to define quantum numbers to solitons by second quantization-like process, clearly distinguishes non topological ones, where vacuum instability means or corresponds to the above Modulation Instability, from topological ones, where an UV divergence on occupation number $(\frac{1}{k})$, is counterbalanced in Energy calculus, the result being a finite energy [9] ; last class seems to be isolated by somewhat Noether constraints and provides probably tools for enforcing criteria on simulations. It is more precised by [], but is intentionally out of the present scope.

Last but not Least, let's invoke a « old hand » reference, as he qualifies himself [14]. Two interesting features emerge from that publication :

1. the distinction between slow -out of resonance- couplings and interactions (propagation, slow light, resonator, . . .) and fast (optical cycles inside medium resonances) , where Physics imposes in either case, a limit of effective time of interplay,
2. associated with it, a great Kerr medium performance may be made inefficient by a limited interaction length

Although overcome by recent innovations, these crude considerations should render us prudent viz portends of the technology.

0.3 THE SILICON NITRIDE SIN, HYDEX AND 2D MATERIALS

0.3.1 Contributions of Si/Sio2 physics

The Si/Sio2 drawbacks has motivated alternative researches, indeed the sensitivity of optical fibers to bending losses induced the invention of highly doped silica glass with oxygen and carbon (Hydex®patent of june 10, 2004). Its technical features are described in [7], ie a linear index of 1.7, low losses of 0.06dB/cm, and a physical behaviour intermediate between silica glass and the nonlinear properties of semiconductors, say a moderate nonlinear Kerr coefficient, but five time larger than those of silica.
The conference of OFC 2003 contains the intervention of Little Optics Inc, who claims a monitored variation of index at fabrication, of 20%. The applications have been fiber-like configurations, wound on PCB for the realization of resonators. However, the typical dimensions of Hydex wave guide on literature are μm sized; moreover, Hydex®is covered by a patent, which does not facilitate academic researches.

In comparison with Si/SiO2 and its precedent impedimenta, wave guides using SIN, immersed inside SiO2, brings beneficial performances.

Indeed, compared with Si/SiO2 [22], with a 10 times larger Kerr coefficient, a large gap $> 2.eV$ assumed at 1550nm [29] losses of 0.03dB/cm against 0.8dB/cm for best SOI wave guides [15], a very low chi^3, Si^3N^4 and its -stoechiometric- variants presents significant qualities for robust wave guides, exposed to large optical power densities, and last but not least, a good compatibility with CMos processes. [5]. A possible restriction [7] is the necessity of high temperature annealing to reduce the propagation losses.

However,despite the SIN performances, a Si/Sio2 description of photonics effects presents an utility :

1. to try to identify physical effects -even described as nonexistent for other materials- in case of large power densities, or fabrication risks,
2. to keep in memory last effects in case of other technological variants
3. to allow a comparison of bare materials with hybrid wave guides described hereafter

0.3.2 2D materials, hybrid wave guides

Extracted from [22], the hybrid wave guides, made of 2D thin films of Metal Dichalcogenides, Graphene family,…covering SIN wave guides, allow a tuning of the non linear interactions; albeit promising, their theoretical and experimental characterizations is not

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[5] In fact, the N element in alloys seems to have been for longtime forgotten from III-V family, being systematically put away from publications. It is interesting to ask if quaternary alloys with N may be envisaged for instance, so a deeper analysis on symmetry group, mesh parameter,…

today precisely determined (except some particular cases).

About numerical determinations, their 2D configuration necessitates high precision meshes for FDTD simulations, or some tricks like in low dimensional meep simulations [6]. Another way to access to nonlinear figures is to link them to surface conductivity. Finally, by experimental procedure like Four Wave Mixing (FWM), given the knowledge of modes mixing, it is possible to access to the -intrinsic- coefficient n_2 of 2D layers.

The γ factor is a key to a methodology, for the performances comparison of these hybrid wave guides, with mixing between nonlinearities and mode configurations ; more specifically, for the sake of practical simulations, it describes the mode confinement induced by 2D high dielectric layers. γ may be fit by comparison between simulations and SPM measurements.

Manufacturing variants and diversity of characterizations are shown to generate a dispersion of recorded performances, joined to above difficulty to determine precisely the non linearity figures. However, the hybrid wave guides have already shown superior performances, seen by Self Phase Modulation (SPM) measurements, ie spectral broadening of the input pulse, a CW laser insuring by a bias, a non linear state inside the wave guide.

For some application, it is attractive to adapt materials with existing second order susceptibility χ^2. As Si, SIN are centrosymetric, so their $\chi^2 \sim 0$, solutions must be found to associate them with other materials. Direct growth of WS2 on SIN by vapor deposition are today research directions for future fabrications modes.

An interesting particular case is the test of 2D Graphene Oxide layers, GO, [34], where the performances of such hybrid wave guides are analysed. the mode overlap is higher for GO on SOI than for GO on SIN or HYDEX, inducing more losses on that configuration. Moreover, it is found that GO on SOI induces more losses than bare SOI, with 2 dB/mm for 2 layers, against 0.4dB/mm. Unfortunately, the comparison table between SOI, and SIN or Hydex is not made with identical wave guide sections, but the calculated n_2 shows in all cases, the benefices of 2D hybrid wave guide, with n_2 ratios four or five decades higher than bare wave guides.

0.3.3 Achievement of a pulse compression

As a suggested reading, the reference [31] illustrates the 1ps/40.62fs compression mechanism and a soliton propagation in a 5.1cm long inversely tapered wave guide (like Horn antenna where matching field impedance is desired), where the exponential width profile with length matches for theoretical dispersion of the solitonic solutions of GNLSE. Dispersion curves and evolution of non linear coefficients with wavelength allow to set the initial operation point, which not always coincides with the zero dispersion one.

For short, comparison is done by simulations, between pure compression and parasitic effects losses, variations of Kerr coefficient,and three photon absorption (3PA). Indeed, above $2\lambda > 2.2\mu$, double photon absorption (TPA) is considered negligible in Si, but in contrast, 3PA starts to appear above input power of $2.2 GW/cm^2$.

It is recorded a compression factor of 24.62 (1ps to 40.62fs FWHM for the pulse width) and a power amplification correspondent, from 0.67W to 16.61W. Parasitic effects raise the pulse width and lower the output power. It is observed for instance, with a loss of 1dB/cm, a spreading of 130.44fs and 1.62W instead of precedent ideal figures.

If the frame of that publication differs from our present scope, with a 2490μ wavelength choice -not in C-band range of Telecom- and with a wave guide taper made in bare Si, it owns a value as compression demonstrator.

Another remark (on the form ?) concerns the claimed self-similar class of wave compression. Indeed, self similarity define wave forms which generally, time envelope and spectrum vary homothetically but converge to a precise analytical form during propagation[8], whatever initial input shape, and doesn't depend of precise input power, while for optical solitons analytical solutions need an additional condition for input power for their stability, in the configuration of [31], either by soliton fission (anomalous dispersion) or by breaking shape (normal dispersion).

The strange attractor feature constituted by true self-similar waves, is to link with homotopy classes described above. One could argue, that the medium for true self-similar waves is those of active fiber amplifier, but self-similarity applies a priori mathematically to a great set of nonlinear equations, including standard solitons. In the mid-infrared compression example, the self-similarity should be then more detailed viz stability, given the maximum power of 0.67W.

That stability is certainly a prerequisite of a well done solitonic design ; also for standard solitons at less, the analytical choice of input waveform may be determinant, particularly its chirp control. It is suggested firstly the transformation to a true similar wave, followed by a compression, to reach that stability. Practically, the first transformation could be realized at the laser level.

0.4 INTEGRATION OF LASER

Actually, there remains an important part, to achieve a full transmission and compression, then the Laser source integration. Fortunately we dispose of ps range Lasers, and bonding techniques become mature. However they present drawbacks, as we meet them in electronics : low reliability, low robustness, complexity/cost of industrial integration, and above all, poor definition of signal transmission via ill-defined wave guide portions. In a first part, is discussed standard techniques, and in second one, possible technological advances, shortly a deep integration inside the material.

0.4.1 Standard techniques

Leaving apart the cumbersome power lasers (gas, dyes, solid barrels,...), the standard techniques for CMos platform rely essentially on bonding or epitaxial growth, last techniques presenting several issues. See herafter.

0.4.2 Attempts to close SI integration of Laser

Beside past developments, [30], results show in [26], the pulsed -and CW performances of an integrated Q-switched Laser source, avoiding any bonding, and seamless. The optical pump and signal are provided from external sources, and the cavity is made from a compact length of SIN guide, with covered by gain materials, realizing also the saturable absorber function. The switching of the cavity Q is insured by two directional couplers. The system works as an astable relaxation oscillator.

The width of output pulses are 250 ns range, with 150nJ per pulse at $1.89 \mu m$ (so a peak power by pulse of $\sim 1W?$). The entire device has a $9mm^2$ footprint, and needs 400mW pump power, with a lasing threshold of 20mW.

The wave guide integration is a strong argument for adapting to a compression transmission line, made with analog wave guides, so transitions should not need lenses and so on. It is claimed a possible scaling at $1.55 \mu m$, sub nanosecond (ps) pulses but with restrictions on max power applied on saturable absorber. However, they seem to remain issues to raise/reduce the output signal/pump power.

To try-and-succeed in a technological rupture, about solid state new materials, then to create a new integrated laser from scratch, is a risky hypothesis inside a 3 years work. It is resumed by [2] in these terms :

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Il faut noter que le développement d'un matériau, non linéaire en particulier,
 nécessite environ dix années d'études, depuis sa découverte
 jusqu'à son utilisation effective dans des systèmes laser commerciaux
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0.5 INVERSE DESIGN SIMULATION AND DEEP LEARNING

0.5.1 Inverse techniques for partial differential equations, and particularly for electromagnetic problems

Scanning a tiny portion of literature on both of these topics, reveals that inverse techniques and Deep learning are today deeply intricate. However, I met inverse techniques for Electromagnetism, used by themselves, at two occasions :

1. for Antenna designs and specifically for magnetic source for Navy [4]
2. for Accelerator on a Chip design [24], that discipline having, in addition, several common technical sides with Photonics

For short, inverse techniques starts from a specified environment, thermal, acoustic, electromagnetic, . . . to come back to the sources. For instance, starting from electromagnetic fields recorded or computed, to determine the antenna characteristics, geometry, current density,. . . .

Naturally, stated like that, the problem should not be bijective (different -sometimes infinity- sources could emit the same field). Photonics applications on SOI incorporate for instance additional given data, often the hard support and the source geometry[23], [12] , so the inverse technique limits the original set in order to define an associated bijection to the initial surjection.

0.5.2 Deep learning associated with it

The goal is now to examine the entire process, ie the application of Deep Learning (DL) techniques to the determination of design by inverse techniques. DL is a subset of Artificial Intelligence, and is described by such a -1185 pages- compilation [32].

More interesting is to focus on a « rough introduction », [13], where precious advises prevent us to use DL with the knowledge of its power and shortcomings. Very shortly, emphasis is on convergence, local and global minima and over fitting, data normalisation, supporting a panel of techniques for designing Neural Networks.

The above mentioned bijectivity is better precised with link with « latent spaces », which reduces the design parameters space to a compact one. Another interesting way -among lot of methods- seems the direct-inverse method.

The recent literature reveals many projects dealing with isolated optical components; a random research on it, adding to already cited [23], [12], gives us for instance, [33] for plasmonic guide design, for multi-layer design [19] where some remarks about algorithms may emerge :

1. Genetic algorithm, associated with randomized geometry with Monte Carlo runs, is the first step to building of a direct Neural network ; interestingly, that network may be mathematically inverted to be the brick of direct-inverse design, may be one shot one, if optimized,
2. Enlarging the design space (optoGPT) has the advantage of global design, but is adversarial to efficient -specific- design, at a high cost,

0.5.3 inspection of DL tools with Python and family

The recommendations of [13] have been adopted for a first inspection and evaluation of Python softwares for DL.

Pymoosh, [5], is based on a classical bridge between multistage filter designs and Bragg networks. Its functioning is simply the extensive use of S-T-Y. . . matrices. There is nothing to add with that, many software are capable to the same tasks, with or without Python. Keras [27] is less trivial, it brings a library usable in Python as is. Identification of common points drives us likely toward Generative Deep Learning. A set of functions may be add to a Python script, for instance in a latent space mode for data sets treatment. Similarly to Pymoosh, the Nevergrad optimizer [1] has many competitors, from C to Julia, knowing that subject having already a long history.

Shortly, there is no « deep learning curve » to use such libraries with Python, except a minimum effort to penetrate the latent space mechanics.

0.5.4 To put an end with Python/Ansys

All following is well documented, and will not be cited here, it is easy to be self informed/alerted of it. I use unfortunately Python and Ansys since several years, so I am able to discuss of it.

Python - a 1980 old language- is known to be today the unique way imposed in Industry ; Google and Meta make a great pressure for its every time adoption. Its pedagogic character is attractive in academic and scientific communities, and several Photonics publications use Python tools. Some programming facilities allow a good training for newbies.

Unfortunately, It is well known that Python is slow comparatively to C or Julia. Consecutively, Benchmarks show also a bad ecological performances, in consumed energy by run. Python is not the language of the Future.

Dealing with Ansys, a 15kEu/year licensed FDTD, we must recognized its capability to manage complex meshes. Adaptive meshing, is his strength. Feedback about it, experienced me that this feature is obviously useful for plagued surfaces or volumes.

However, Photonics geometries for wave guides are generally 2D cylindrical, planes, with a few accidents, which does not necessitate adaptive meshing, knowing that it slows very much the simulations. Today many small pieces of **free** softwares may replace Ansys for these electromagnetic tasks, with equivalent precision and faster performances. It is worth to pay attention to it, although the choice Ansys/Other is not so evident that with Python.

0.6 CONCLUSION

Inside that short bibliography, we've travelled among the promising avenues of Photonics on Cmos platforms. Their waited tremendous performances, 100GHz rate, mm^2 layout, pJ consumption, allow a large computing power at minimum cost, the production of entirely new chips with AI integrated inside, and are compatible with an ecological world, letting far away the present signal electronics.

Observing that real conceptual technologic revolution, we can't ignore the present research issues. The pure Cmos platform with SOI, studied since decades, show some impedimenta like free charge carriers and two-photon absorption. Other platforms like InP remain devoted to specific projects, and are probably too costly for industrial production, so CMos platform are today highlighted by many researchers, through improvments.

Among them, SIN on silicon substitutes for instance, doesn't suffer from above impedimenta, but optical mode confinement stays insufficient to allow solitonic signal propagation, which may be one condition of high rates. The current tendancy is to beneficiate from thin films thanks to lithography and etching. The corresponding physics of somewhat not entirely known materials, and propagation in non homogeneous wave guides is left to be deeper mastered. This objective will be probably insured in next decade.

Let's note the close correspondances with Accelerator on a chip, research initiated still 2013 by Stanford, and followed by many international countries and labs (ACHIP project). Indeed, Inverse techniques and photonics are largely used for the definition and design of electron beams inside tiny wave guides, accelerated by low cost lasers. Accelerator on a chip, will certainly replace cumbersome and costly « big instruments ». The transition may be painful for scientific organisations and countries not prepared to.

Bibliographie

[1] How to perform optimization — nevergrad documentation, February 2024. [Online ; accessed 11. Mar. 2024].

[2] Gérard Aka and Pascal Loiseau. Les nouveaux matériaux laser et non linéaires : état de l'art. *Photoniques*, (69) :24–30, January 2014.

[3] Andrea Blanco-Redondo, C. Martijn de Sterke, J. E. Sipe, Thomas F. Krauss, Benjamin J. Eggleton, and Chad Husko. Pure-quartic solitons. *Nat. Commun.*, 7(10427) :1–9, January 2016.

[4] Olivier Chadebec. *Modélisation électromagnétique basse fréquence, identification de sources équivalentes et métrologie en champs magnétiques faibles.* PhD thesis, Université de, Grenoble, France, October 2011.

[5] Josselin Defrance, Caroline Lemaître, Rabih Ajib, Jessica Benedicto, Emilien Mallet, Rémi Pollès, Jean-Pierre Plumey, Martine Mihailovic, Emmanuel Centeno, Cristian Ciracì, David R. Smith, and Antoine Moreau. Moosh : A Numerical Swiss Army Knife for the Optics of Multilayers in Octave/Matlab. *Ubiquity Press*, 4(1), April 2016.

[6] Meep Developers. Tutorial/Eigenmode Source - MEEP Documentation, January 2024. [Online ; accessed 8. Feb. 2024].

[7] David Duchesne, Marcello Ferrera, Luca Razzari, Roberto Morandotti, Brent Little, Sai T. Chu, and David J. Moss. Hydex Glass : a CMOS Compatible Platform for Integrated Waveguide Structures for Nonlinear Optics. *arXiv*, May 2015.

[8] John M. Dudley, Christophe Finot, David J. Richardson, and Guy Millot. Self-similarity in ultrafast nonlinear optics. *Nat. Phys.*, 3 :597–603, September 2007.

[9] Gia Dvali, Cesar Gomez, Lukas Gruending, and Tehseen Rug. Towards a quantum theory of solitons. *Nucl. Phys. B*, 901 :338–353, December 2015.

[10] H. Y. Fan. Chapter 9 Effects of Free Carriers on the Optical Properties. In *Semiconductors and Semimetals*, volume 3, pages 405–419. Elsevier, Walthm, MA, USA, January 1967.

[11] P. M. Fauchet, D. Hulin, R. Vanderhaghen, A. Mourchid, and W. L. Nighan. The properties of free carriers in amorphous silicon. *J. Non-Cryst. Solids*, 141 :76–87, January 1992.

[12] Jakob S. Jensen and Ole Sigmund. Topology optimization of photonic crystal structures : A high-bandwidth low-loss T-junction waveguide. *Journal of The Optical Society of America B-optical Physics - J OPT SOC AM B-OPT PHYSICS*, 22(6), June 2005.

[13] Abdourahman Khaireh-Walieh, Denis Langevin, Pauline Bennet, Olivier Teytaud, Antoine Moreau, and Peter R. Wiecha. A newcomer's guide to deep learning for inverse design in nano-photonics. *Nanophotonics*, 12(24) :4387–4414, November 2023.

[14] Jacob B. Khurgin. Nonlinear Optics : a look from the interaction time viewpoint and what it portends. *arXiv*, July 2022.

[15] Kevin K. Lee, D. Lim, L. Kimerling, Jangho Shin, and F. Cerrina. Fabrication of ultralow-loss Si/SiO(2) waveguides by roughness reduction. *Opt. Lett.*, 2001.

[16] J. Leuthold, C. Koos, and W. Freude. Nonlinear silicon photonics. *Nat. Photonics*, 4 :535–544, August 2010.

[17] Q. Lin, Oskar J. Painter, and Govind P. Agrawal. Nonlinear optical phenomena in silicon waveguides : Modeling and applications. *Opt. Express*, 15(25) :16604–16644, December 2007.

[18] Wu-Ming Liu and Emmanuel Kengne. Overview of Nonlinear Schrödinger Equations. In *Schrödinger Equations in Nonlinear Systems*, pages 1–13. Springer, Singapore, March 2019.

[19] Taigao Ma, Haozhu Wang, and L. Jay Guo. Optogpt : A foundation model for inverse design in optical multilayer thin film structures, 2023.

[20] mordorintelligence.com. Analyse de la taille et de la part du marché de la photonique sur silicium - Rapport de recherche de l'industrie - Tendances de croissance, February 2024. [Online ; accessed 2. Feb. 2024].

[21] Charles Nash and Siddhartha Sen. *Topology and Geometry for Physicists.* Academic Press, 1983.

[22] Vincent Pelgrin, Hoon Hahn Yoon, Eric Cassan, and Zhipei Sun. Hybrid integration of 2D materials for on-chip nonlinear photonics. *gxjzz*, 4(3) :311–333, December 2023.

[23] Alexander Y. Piggott, Jesse Lu, Thomas M. Babinec, Konstantinos G. Lagoudakis, Jan Petykiewicz, and Jelena Vučković. Inverse design and implementation of a wavelength demultiplexing grating coupler. *Sci. Rep.*, 4(7210) :1–5, November 2014.

[24] Neil V. Sapra, Ki Youl Yang, Dries Vercruysse, Kenneth J. Leedle, Dylan S. Black, R. Joel England, Logan Su, Rahul Trivedi, Yu Miao, Olav Solgaard, Robert L. Byer, and Jelena Vučković. On-chip integrated laser-driven particle accelerator. *Science*, 367(6473) :79–83, January 2020.

[25] Gary F. Sinclair, Nicola A. Tyler, Döndü Sahin, Jorge Barreto, and Mark G. Thompson. Temperature Dependence of the Kerr Nonlinearity and Two-Photon Absorption in a Silicon Waveguide at 1.55 μm. *Phys. Rev. Appl.*, 11(4) :044084, April 2019.

[26] Neetesh Singh, Jan Lorenzen, Milan Sinobad, Kai Wang, Andreas C. Liapis, Henry C. Frankis, Stefanie Haugg, Henry Francis, Jose Carreira, Michael Geiselmann, Mahmoud A. Gaafar, Tobias Herr, Jonathan D. B. Bradley, Zhipei Sun, Sonia M. Garcia-Blanco, and Franz X. Kärtner. Silicon photonics-based high-energy passively Q-switched laser. *Nat. Photonics*, pages 1–7, February 2024.

[27] Keras Team. Keras documentation : A walk through latent space with Stable Diffusion, January 2024. [Online ; accessed 11. Mar. 2024].

[28] David J. Thomson, Aaron J. Zilkie, John Edward Bowers, Tin Komljenovic, Graham T. Reed, Laurent Vivien, Delphine Marris-Morini, Eric Cassan, Léopold Virot, Jean-Marc Fédéli, J M Hartmann, Jens H. Schmid, Danxia Xu, Frédéric Boeuf, Peter A. O'Brien, Goran Z. Mashanovich, and Milos Srecko Nedeljkovic. Roadmap on silicon photonics. *Journal of Optics*, 18, 2016.

[29] Shu-Ju Tsai, Chiang-Lun Wang, Hung-Chun Lee, Chun-Yeh Lin, Jhih-Wei Chen, Hong-Wei Shiu, Lo-Yueh Chang, Han-Ting Hsueh, Hung-Ying Chen, Jyun-Yu Tsai, Ying-Hsin Lu, Ting-Chang Chang, Li-Wei Tu, Hsisheng Teng, Yi-Chun Chen, Chia-Hao Chen, and Chung-Lin Wu. Approaching Defect-free Amorphous Silicon Nitride by Plasma-assisted Atomic Beam Deposition for High Performance Gate Dielectric. *Sci. Rep.*, 6(28326) :1–9, June 2016.

[30] Chao Xiang, Joel Guo, Warren Jin, Lue Wu, Jonathan Peters, Weiqiang Xie, Lin Chang, Boqiang Shen, Heming Wang, Qi-Fan Yang, David Kinghorn, Mario Paniccia, Kerry J. Vahala, Paul A. Morton, and John E. Bowers. High-performance lasers for fully integrated silicon nitride photonics. *Nat. Commun.*, 12(6650) :1–8, November 2021.

[31] Jin-Hui Yuan, Jian Chen, Feng Li, Chao Mei, Zhe Kang, Xianting Zhang, Yin Xu, Binbin Yan, Xinzhu Sang, Qiang Wu, Xian Zhou, Kangping Zhong, Kuiru Wang, Chenxue Yu, Gerald Farrell, and P.K.A. Wai. Mid-infrared self-similar compression of picosecond pulse in an inversely tapered silicon ridge waveguide. *Optics Express*, 25 :33439, 12 2017.

[32] Aston Zhang, Zachary C. Lipton, Mu Li, and Alexander J. Smola. Dive into Deep Learning. *arXiv*, June 2021.

[33] Tian Zhang, Jia Wang, Qi Liu, Jinzan Zhou, Jian Dai, Xu Han, Yue Zhou, and Kun Xu. Efficient spectrum prediction and inverse design for plasmonic waveguide systems based on artificial neural networks. *Photonics Research*, 7 :368, 03 2019.

[34] Yuning Zhang, Jiayang Wu, Yunyi Yang, Yang Qu, Linnan Jia, Baohua Jia, and David J. Moss. Enhanced spectral broadening of femtosecond optical pulses in silicon nanowires integrated with 2d graphene oxide films. *Micromachines*, 13(5) :756, May 2022.