

Active planar lightwave devices for optical signal processing

P. Boffi^{1,2}, R. Costa¹, M. Ferrario¹, A. Melloni^{1,2}, F. Morichetti¹, D. Piccinin¹, M. Ubaldi¹, S. M. Pietralunga¹

¹CoreCom, Via G. Colombo, 81, 20133 Milano, Italy

²Politecnico di Milano, Dpt. Elettronica e Informazione, v. Ponzio 34/5, 20133 Milano, Italy

Time-domain numerical analysis of nonlinear propagation in Slow-Wave-Structures, focused on the interplay of enhanced third-order nonlinearity with chromatic dispersion has been carried on. In dependence on the operating conditions, a tunable optical oscillator/pulse train generator and an optical limiter have been designed. Morphological inspection and functional characterization at $\lambda=1.5 \mu\text{m}$ of fibre-optic coupled PMMA optical waveguides, containing Er-doped nanoclusters, was performed, as contribution to first demonstration of net amplification in PMMA planar waveguide devices in the third communication window. An experimental research activity on nanostructured ordered porous alumina films of good optical quality was also started.

1. INTRODUCTION

Since its birth, the mission of CoreCom, which is a private non-profit Research Consortium established in 1995 as a joint venture of Italian Technical University in Milan, *Politecnico di Milano*, and *Pirelli Company*, has been to perform advanced research in the field of processing and switching of optical signals for communications. This has led to the constitution of several Laboratories, dealing with all research aspects related to optical communications, from the optimisation of optical network topology and protocols, to the emulation of innovative optical transmission systems, to the design and test of optical devices and the growth, processing and characterization of optical materials. In particular, the Integrated Optics Lab and the Optical Technologies Lab have been working for several years on the miniaturization of optical signal processing functions, and more specifically on the design and characterization of planar lightwave integrated circuits, as well as other technological solutions for Wavelength Division Multiplexed (WDM) systems.

The contribution given by CoreCom to research within the frame of Phoremest in the first 12 months of activity was mainly comprised within *WorkPackage 18-Optical Signal Processing*, and addressed mainly to the performance evaluation and test of active optical planar waveguide devices, performing optical processing functions such as optical limiting, pulse train generation, optical amplification. In particular, a theoretical analysis on nonlinear optical propagation in Slow Wave Structures (SWS) made of cascaded integrated-optics resonators was performed, from the point of view of the optical circuit; this will be detailed in Section II. Section III will illustrate the contribution given by CoreCom in characterizing Er-doped polymeric waveguide amplifiers, in a joint research activity with ENS-Cachan. Finally, Section IV will illustrate some preliminary results of a research program, independently established in CoreCom in the past few months and now seeking for partnership within Phoremest, related to the production and characterization of ordered nanostructured porous aluminium oxide.

2. NONLINEAR OPTICAL PROPAGATION IN SWS

Nonlinearities in coupled-resonator optical structures, like those shown in Fig. 1, have been deeply investigated in recent literature for applications in the field of optical signal processing and particular interest has been devoted to the possibility to enhance the nonlinear phase-shift [1-3] to deploy bistability effects [1,3] and to increase the efficiency of second harmonic generation [4] and wavelength conversion based on four-wave-mixing [5]. Actually, inside the passing bands of a Slow-Wave Structure (SWS) consisting of a chain of directly coupled resonators, both chromatic dispersion and nonlinearities are dramatically enhanced, as a consequence of optical slow-wave propagation [6]. The effective nonlinear coefficient $n_{2,eff}$ in SWS is S^2 times the n_2 of the bulk material, being S the slowing ratio given by the structure. Combinations of different architectures of slow-wave structures have been proposed to reduce and/or optimise the chromatic dispersion given by the structure inside the passing band, while keeping the nonlinearity enhanced [7]. In this way it is demonstrated the possibility to expand the effective bandwidth of the coupled-resonator structure. Moreover, a discrete-time signal processing approach has been suggested for the synthesis of coupled-resonator based devices with a desired non-linear phase-shift response [8].

When Phoremest activity started, only the steady-state behaviour of SWSs in the non-linear regime had been investigated and no analysis of the dynamic behaviour had been reported yet.

The main contribution of Integrated Optics Lab of CoreCom have been related to the numerical investigation of dynamic nonlinear propagation in SWSs, mainly focusing on dynamic self-phase modulation effects based on the interplay between optical nonlinearities and the chromatic dispersion introduced by the SWS.

Fig. 2 shows the effects of nonlinear propagation in SWS, in dependence of spectral features of input signal. In Fig. 2(a) the slowing factor versus frequency of a 10 cavities long SWS is shown; the group delay has a minimum value at the resonance frequency f_0 and rapidly increases moving towards the band edges, so that at resonance the second order dispersion χ_2 vanishes, whereas a convenient dispersion can be introduced when the input signal is detuned from f_0 . In the nonlinear regime, the spectral response tends to be left-shifted by the Kerr effect and optical propagation is substantially different for signals centred at frequencies f_A or f_B . For an input step signal tuned on the left of the central frequency, f_0 , the output signal starts to rapidly oscillate, as shown in Fig. 2(b). This oscillation is due to the strong SWS anomalous dispersion that is responsible for modulation instability phenomena. For sufficiently high input power, the oscillation frequency equals the distance f_{MI} between the left-end band edge and f_A , since the left-side peak of the group delay drives the maximum gain for modulation instability. An adjustable optical oscillator or a pulse train generator can be realized, whose repetition rate can be controlled by suitably tuning the SWS spectral response with respect to the input signal. On the contrary, a stable time evolution is observed for input signals tuned at f_B . In this case, as power is increased, an input signal experiences a higher slowing factor and is drifted further to the rightmost side of the band-pass. Near the edge a natural steady state is reached, because the portion of the signal in excess is backward reflected and the output transmitted power is limited to a maximum value that depends on the detuning $\Delta f = f_B - f_0$. Fig. 1(c) shows the output signals obtained for the indicated step input signal for different Δf . By increasing Δf the maximum output power decreases. The output signal is delayed with respect to the input and after a small transient stabilizes around the final value that does not depend on the input power, realizing a tunable optical limiter.

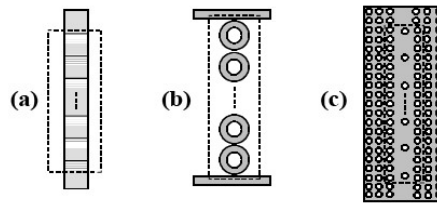


FIG. 1: Examples of direct-coupled optical resonator SWS; (a): direct coupled Fabry-Perot; (b): SWS direct coupled microring SWS; (c): PBG-SWS.

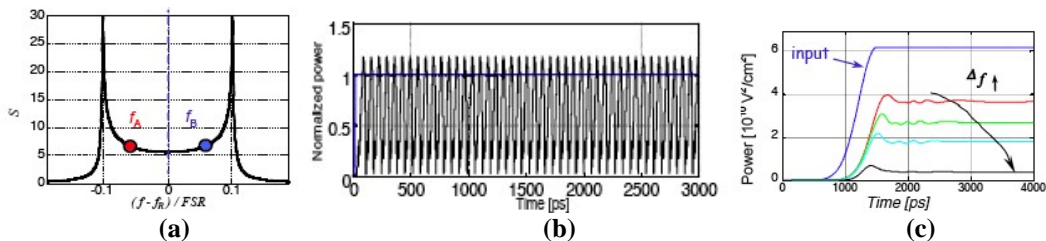


FIG. 2: (a): Slowing ratio S vs. f of a 10-resonators SWS with finesse $F = 5$. (b): Oscillating output signal of a SWS for an input step signal tuned at f_A ; (c): optical limiting effect for an input step signal tuned at f_B .

3. CHARACTERIZATION OF POLYMERIC AMPLIFIERS AT $\lambda=1.5 \mu\text{m}$

Optical amplification without the need for electronic regeneration of the signal is a key function both in long-haul optical communication systems and whenever the existence of splitting or loss require the restoration of the original optical power level. Polymeric materials are currently used, to produce low-cost optical fibers and are investigated as a promising technology to realize low-cost-high-volume planar optical circuits. The technological exploitation of organic materials to the processing of signals in the first communication window around $0.8 \mu\text{m}$ is the more straightforward, as usually propagation is affected by low optical loss level. On the contrary, in order to extend the use of plastic optics to the third window at $1.5 \mu\text{m}$, more research efforts are required, mainly in view of overcoming the high level of loss affecting optical propagation in this spectral range. Besides chemical modifications of the polymeric chains, like for instance deuteration, aimed at removing the presence of chemical bonds at the origin of loss, the introduction of effective optical amplification is of course a key point to cancel the effect of attenuation and, moreover, it opens the perspective of the realization of fully-equipped polymeric planar optical circuits.

In this challenging field of research, Prof. Isabelle Ledoux and co-workers at *ENS-Cachan* have been working for some time, first by proposing innovative methods to effectively incorporating Erbium ions into polymeric matrices and then by realizing first-trial prototypes of waveguiding structures.

CoreCom has joined ENS-Cachan in this activity, by experimentally supporting the characterization of Er-doped PMMA rib waveguides, used as optical amplifiers in the 1.5 μm range. Prototype waveguides were tested in a fiber-optic testbed, equipped with nanopositioners to evaluate the performances of planar lightwave circuits and the efficiency of coupling to single-mode optical fibers. Optical signal and pump were provided by semiconductor lasers, the laser at 1.5 μm being tunable on the third communication window range for best matching of transmission and amplification characteristics of waveguides. Fiber-optic Wavelength Division Multiplexers (WDM) couplers were used to multiplex signal and pump at the input of the waveguides under test, and to demultiplex the amplified signal from residual pump at the output. The coupling of light into and out of the waveguide samples were accomplished by means of small-core fiber sections, fusion spliced to standard fibers which constitute the rest of the testing set-up. Performances in transmission and amplification were measured using alternatively an Optical Spectrum Analyzer and an optical power meter. Optical pumping at both 1480nm and 980nm was tested; while the former turned out not to be effective, under 30mW pumping at 980nm, up to 1dB/cm gain was demonstrated.

Rib waveguides in PMMA had been realized at ENS Cachan, by optical lithography and reactive ion etching. In Fig. 3 we report a SEM picture of the waveguide section and a picture of the optical output at 1.5 μm . In spite of the high lateral surface roughness introduced by the RIE process, which needs to be optimised, intrinsic losses amount to less than 1.4 dB/cm and good single-mode behaviour was experimentally proven, as suggested by the optical output as recorded by a CCD camera and shown in Fig. 3.

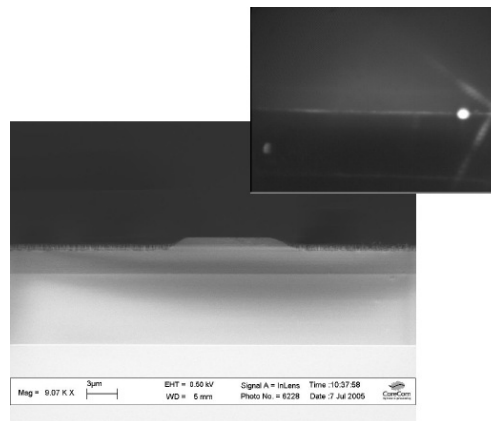


FIG. 3: Single-mode RIE-etched amplifying waveguides in Er-doped PMMA: SEM image and optical output from fibre coupling at $\lambda=1.5 \mu\text{m}$.

4. NANOSTRUCTURED OXIDE FILMS

In these latest months, a new research program was established in CoreCom, related to the production and characterization of ordered nanostructured porous anodic aluminium oxide (porous alumina). Porous alumina is well known as an interesting inorganic template to grow metal nanowires and also as a host for either active or magneto-optic materials [9,10]. Its self-assembled nanostructure can be conditioned so as to result into an ordered 2D periodic lattice (photonic crystal) showing promising effects on the optical density of states [11]. One of the problems of self-assembled porous alumina is the surface roughness, which must be minimized if a good optical-quality material is to be obtained; one other issue is to obtain large-scale ordered periodic 2D structures in a short time and at reasonably low cost. CoreCom is working on the realization of smooth alumina films, by anodization of optical quality aluminium layers on suitable substrates. Regarding the second aspect, pre-patterning of aluminium was used, prior to anodization, by exploiting as molds diffractive gratings [12]. Examples of preliminary results are shown in Fig. 4.

Some first characterizations on the 2D photonic crystal behaviour were performed by spectrally resolved reflectivity measurements. Examples of results are given in Fig. 5, showing the comparison with simulated reflection peaks for a periodic 2D hexagonal lattice of analogous spacing, pore diameters and refractive index contrast.

As porous alumina is already considered as a research subject within Phoremest, namely in WP11 and WP12, CoreCom is willing to establish research partnerships within Phoremest on this subject, and actually some shared interest for a joint activity has been found with IMAPh institute (Minsk-Belarus).

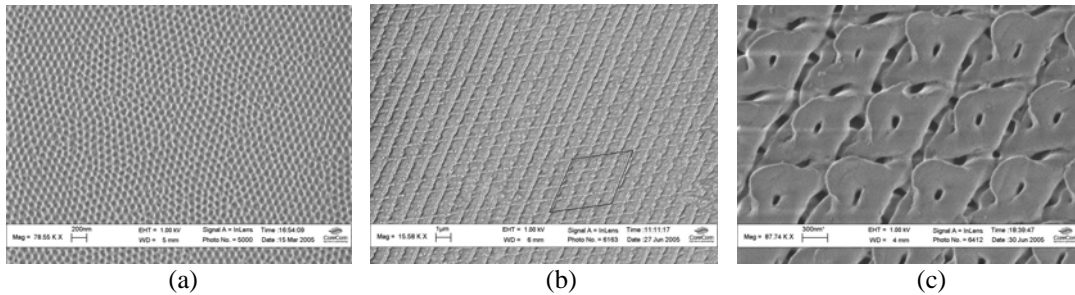


FIG. 4: Samples of anodic aluminium porous oxide obtained in phosphoric acid. (a): partial ordering by two-steps anodization of an aluminium foil 99,995%; (b): hexagonal ordered 2D lattice, obtained by pre-patterning of the aluminium foil, using 60°-rotated gratings as molds; (c) detail of surface for the sample in (b).

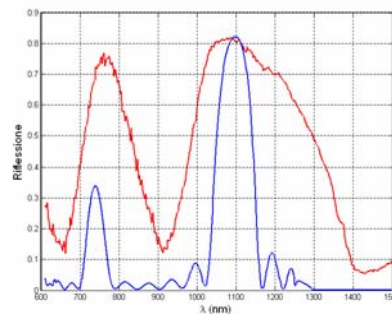


FIG. 5: Experimental reflectance spectrum at 40° of incidence, confronted with simulated spectrum for the coefficient of reflection. Simulated 2D structure has a lattice of air pores in a matrix of refractive index $n=1.67$ and filling factor $f=0.15$.

5. CONCLUSIONS

CoreCom has participated to Phoremest Joint Research Activities in the first year, by performing dynamic simulation of non-linear propagation in coupled resonating structures, to be eventually implemented by means of either photonic crystal structures, or coupled cavities like gratings or ring waveguides; experimental characterization of PMMA-based waveguide amplifiers at $1.5\mu\text{m}$ has also been started, as joint research with ENS-Cachan. The testing of porous alumina templates to be used as nano-structured optical devices is also another field of research where partnerships within the Network of Excellence can be established.

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