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INTEGRATED OPTICS APPLIED TO ASTRONOMICAL APERTURE SYNTHESIS: III. SIMULATION OF COMPONENTS OPTIMIZED FOR ASTRONOMICAL INTERFEROMETRY

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ABSTRACT - *Astronomical aperture synthesis requires to combine beams coming from telescopes, with constraints on mechanical and thermal stability, sensibility, accuracy on the mesurement of visibility of the interferences. One adapted way for solving the problem is integrated planar optics. For this application, glass ion exchange can be considered. Often used for telecom applications, the capabilities of interferometers must be adapted to astronomical constraints. An interferometer of this type is currently used at the Laboratoire d'Astrophysique de l'Observatoire de Grenoble, with improvable transmission. After a brief presentation of the guided modes in integrated optics, this article describes various interferometers and a method of simulation to evaluate their behavior vs. the wavelength and the polarization.*

1 - INTRODUCTION

Astronomical aperture synthesis is a new promising observation method which implies real important efforts in research and development. Astronomical interferometers have already been made with guided optics. Moreover, since 1996 and the astrofib'96 meeting [Kern 96], it appears that integrated optics applied to astronomical interferometry might have interesting features. The reader can refer to Kern & al [Kern 97] for a general overview of integrated capabilities and to Berger & al [Berg. 97] for the first laboratory results. The key function of astronomical aperture synthesis is the combination of beams collected by different subapertures. The aim of this paper is to look in more details at the behavior of integrated optics within this context. In section 2, we present the theory of local coupling modes, which allows us to understand the mechanisms which occur in integrated structures. Section 3 describes the Y-coupler, the most used component in telecom application. Other ways to combine several beams are discussed in section 4. Finally, section 5 presents methods of simulation and gives examples.

2 - THE LOCAL COUPLING MODES IN INTEGRATED OPTICS

2.1-The local modes

In a straight multimode waveguide, orthogonal eigenmodes propagate at constant amplitude In a structure whose geometric profile varies along the propagation axis, the formalism of the local modes is used At a fixed position, the local mode of the structure is equal to one eigenmode of the straight waveguide of the same width as the structure at this position (Fig 1 a, see [Marc. 74])

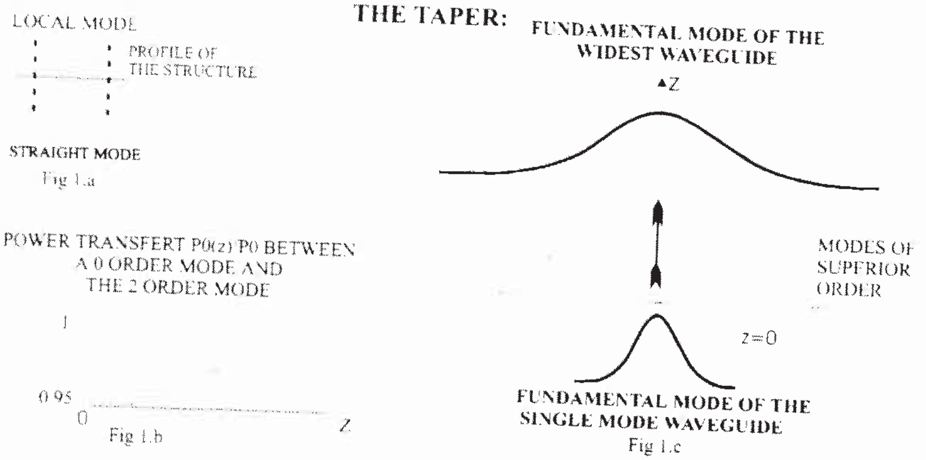

Fig 1.a

Fig 1.b

Fig 1.c

Fig. 1: illustration of the theory of local modes: the adiabatic transition.

2.2 -The taper

A taper is a transition between a narrow guide and a wider waveguide. In such a varying structure, modes of order higher than the fundamental one appear The difficult point is to evaluate the beating of energy carried by the input fundamental mode which is coupled on the second and fourth mode (See fig 1 b, [Scha 94]) An **adiabatic** taper is a structure where the whole energy of the input fundamental mode remains at the output on the fundamental mode (By analogy with the thermodynamical adiabatic transformation without heat losses)

2.3 - Modes coupling

When the spacing between two waveguides is important, the structure is composed of two three-layer guides (Fig 2a) and there is no interaction between them When the spacing decreases, the structure is composed of a five-layer waveguide, evanescent fields interact. Each fundamental mode of the waveguides are linearly combined, inducing supermodes. (Fig 2 b)

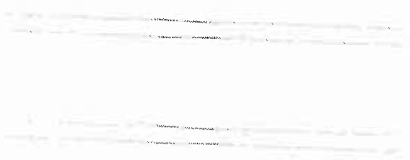

Fig. 2a: Modes in far waveguides

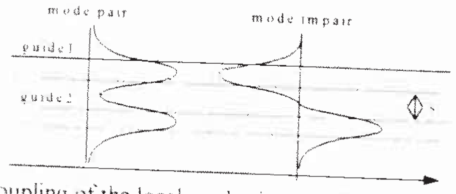

Fig. 2b: Coupling of the local modes in near waveguides

3 - THE Y-JUNCTION

A very good example of this mechanism is the Y-junction [Izut. 82]. This device can work as a 3-dB power divider or a combiner. It is composed of three sections: two monomodal waveguides at the input, one adiabatic taper, and the output monomodal waveguide (Fig 3 a). When used as a combiner, if the signal I is injected in the first input waveguide, 0.5 I is collected at the output resulting from the propagation of the even supermode and 0.5 I composed of the odd supermode is radiated. In a similar way, only 0.5 I is collected if the second input waveguide is excited. If the two input guides are excited, the interferometric signal is obtained at the output.

In fact, when the two inputs are in phase, only the even supermode is excited, and no losses are observed. The problem appears when the inputs are in opposite phase (Fig 3 b).

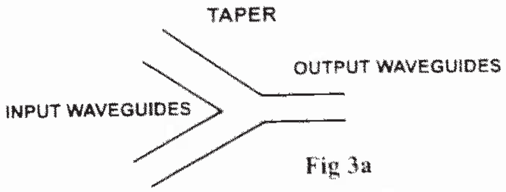

Fig 3a

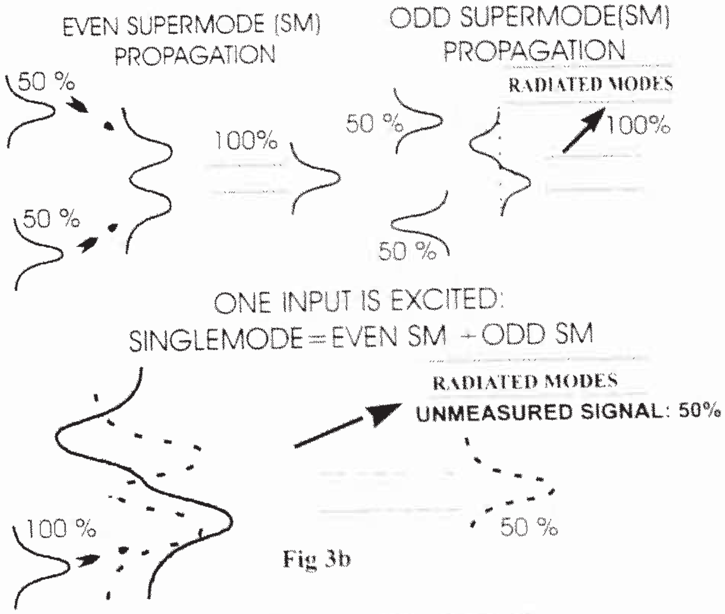

Fig 3b

Fig 3: mechanisms of the Y-junction

The analysis of the Y-junction allows to make three observations

- For an efficient combiner, it is necessary to collect all the light and therefore radiated energy must be collected. **We need a fourth guided-port structure**
- It is useful to recapture the radiated energy notably because the information carried corresponds to signal with phase opposition. Another way to understand why fifty per cent of the light is lost is the analogy with a bulk optics beamsplitter. If the light is only collected at one side of the beamsplitter, 50% of the light is also lost. In both cases, **the interferometric signal suffers of a π phase shift between the two outputs.**

- Moreover, a 0.1% contrast accuracy is expected. It imposes to have two output channels balanced around a 50% recombination with a critical accuracy. **Such an accuracy implies to have a photometric calibration of the two input channels. This can be done by the way of extra-calibration channels.**

⇒ **All these remarks have led us to look for four-port structures.**

4 - OTHER WAYS OF COMBINATION (FIG 4)

Other types of combiners have been tested for two inputs and even for three ones (See fig 4), except for the structure 4 j. The recombiners can be divided in three categories: X-couplers (4b,4c,4d), directional couplers (4e, 4f, 4g) and multiaxial combiners. The latter family will not be studied.

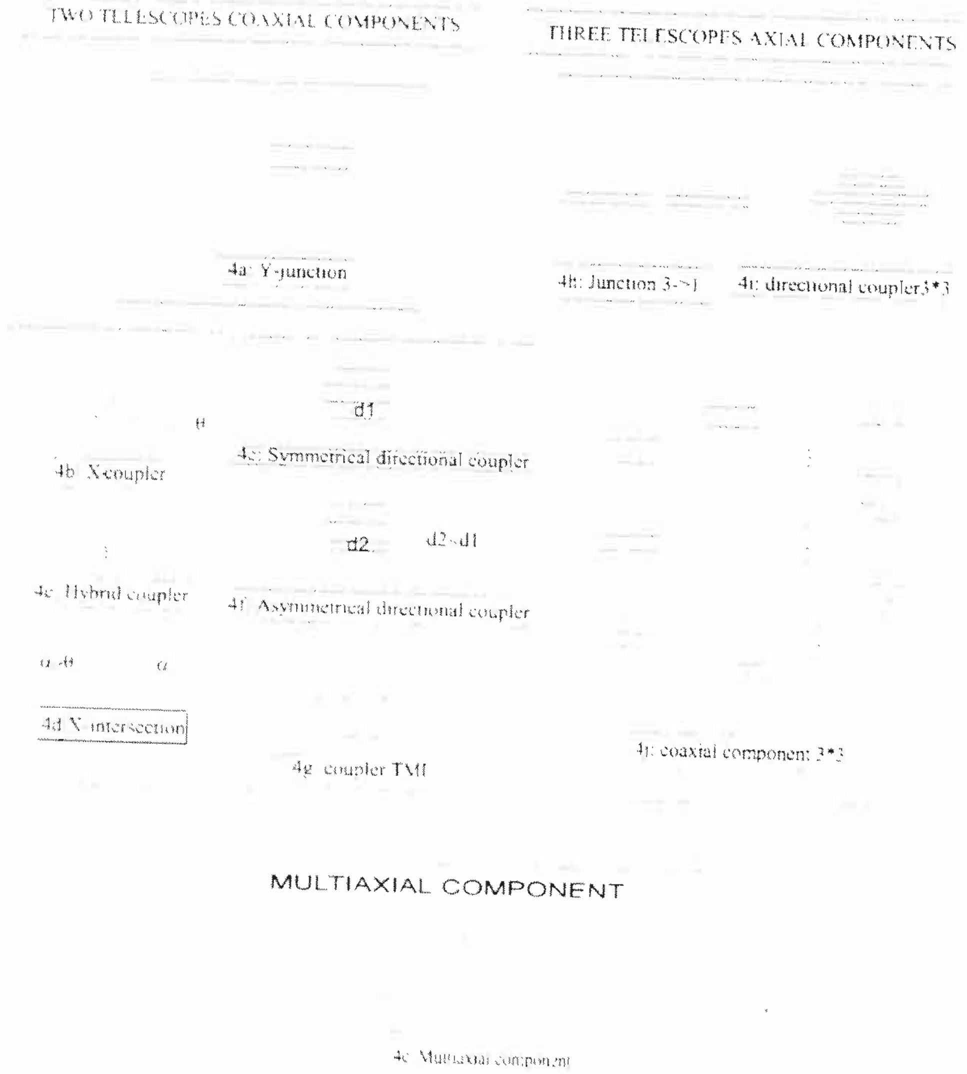

Fig. 4: different types of combiners

4.1 - The X- coupler

We distinguish

- The X-symmetrical coupler (fig 4b, see also fig 5) for low angle of branching (i.e. less than 1 degree, [Gera. 94]), it works as a coupler. One part of the input local modes is radiated at the intersection, as it's too small to guide the two local modes. But one part of the radiation can be coupled with the guiding waves in the output arms, because of the low distance of propagation of the radiative energy. The other part is lost. So we may succeed in having losses lower than with a Y-junction but larger than with a X-asymmetrical coupler (see below). This device is well known and its feasibility has been demonstrated. (See analytic study in [Agra. 87])
- The X-intersection (fig 4.d) for angles larger than 10 degrees [Gera. 94], there is a low crosstalk between the guides and the component does not act as a combiner. This configuration allows to build compact systems with intersecting guides which never interact between themselves

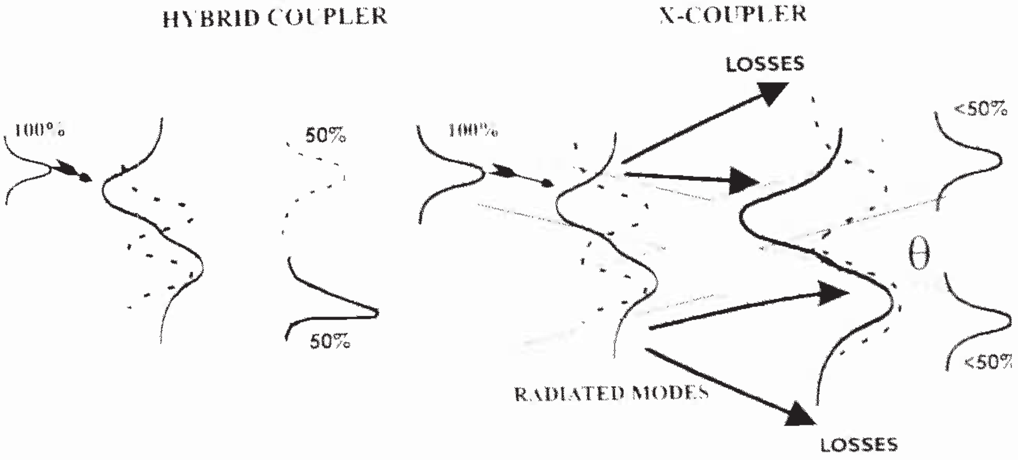

Fig. 5: principle of hybrid and X-couplers

- The X-asymmetrical coupler or hybrid coupler is composed of a symmetrical Y-junction input and an asymmetrical Y-junction output (two guides of different widths), without separation between them ([Izut. 82]). When the inputs are in phase (See also fig 5), the even local mode of the input are converted in the eigenmode of the widest arm, while when the inputs are in opposite phase, the odd local mode is turned in the eigenmode of the smaller one. So we do not loose any signal. If the adiabatic condition is satisfied (i.e. only the modes 0 and 1 appear at the intersection zone), the coupler can be used as a 3-dB power division (and thus as an equal combiner) whatever the wavelength and the polarization. Hussell and al [Huss. 90] have obtained such a power divider at 1.3 µm. They excite one channel and measure an average 3-dB separation on one output with a variation inferior to 0.4 dB on a bandwidth of 150 nm around 1.3 µm. They expected to obtain the same performances for a bandwidth centered on 1.55µm

4.2 - The directional couplers (Fig 4.e, see also fig 6)

Another solution is to use a directional coupler. This device is composed of two guides which can exchange their energy thanks to their low separation distance **s** (Fig 6). If one input is

excited. both supermodes are excited. But they have different phase velocities and so a phase shift is created between them along the propagation. After a length named coupling length L_C, the energy carried by the guide and transferred in the other guide is maximum
In the case of a symmetrical directional coupler, if the length L of the coupler is equal to L_C all the energy of the first guide is transferred since the local modes are in opposite phase in the first arm and in phase in the second one The waveguides have the same width The sum of the two outputs powers is equal to 1

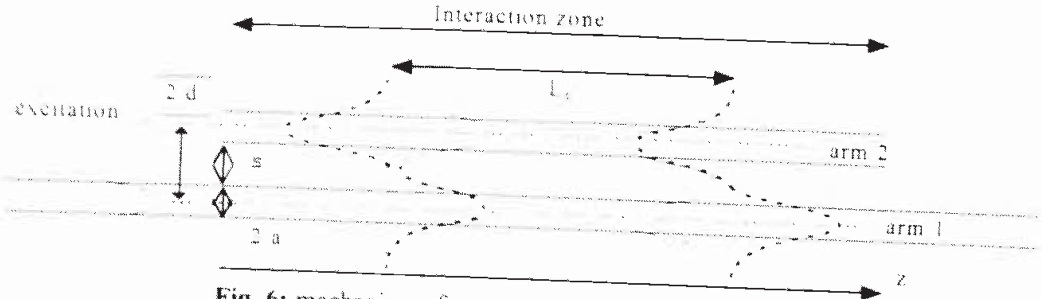

Fig. 6: mechanism of a symmetrical directional coupler

4.2.1 Influence of λ

- The output power have a sinusoidal wavelength dependence For instance, for the two-mode interference coupler (figure 4g), a symmetrical directional coupler where the spacing is nul. the half-period of the curve is equal to

$$\Delta\lambda = \frac{\pi}{L_C\left(\frac{d\beta_{even}}{d\lambda} - \frac{d\beta_{odd}}{d\lambda}\right)} \qquad (4.1)$$

where βeven(odd) is the phase velocity of the even (odd) mode So for large bandwidth components, we must decrease the coupling length or the intermodal dispersion (The difference between the derivatives of each phase velocity at the denominator).

- The optical power is transferred periodically with respect to propagation distance For a 3-dB (i.e. 50%) separation directional coupler, a length of the coupler equal to half the coupling length must be chosen. In the case of symmetrical couplers, the slope of the curve for the 3-dB separation is maximum This implies a high sensitivity to wavelength via the parameter L/Lc The device has limited performances for broadband wavelength applications An asymmetrical directional coupler with two waveguides of different widths provides a good option as its behavior presents a flattened response at 50% and L=Lc (See Fig 7) Therefore the wavelength dependence is expected to be weak

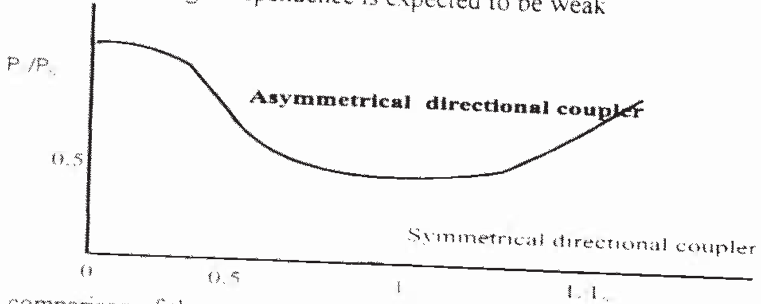

Fig. 7: comparison of the response of the symmetrical and asymmetrical directional couplers. L=length of the coupler, Lc the coupling length

Yanagawa [Yana. 90] defines a bandwidth where a coupling/splitting ratio is within +/- 1 dB around to 3 dB The bandwidth of the symmetrical and asymmetrical couplers are predicted to be 140 nm and more than 300 nm respectively Alternating directional couplers with better bandwidth exist too, but they are more difficult to construct Takagi [Taka. 89] has succeeded to build a broadband silica-band coupler with asymmetric structure showing wavelength flattened coupling ratios of 50% +/- 5% over the 1.2µm-1 6µm bandwidth

4.2.2 Influence of polarization

Apart from the wavelength dependence, the two main problems are the reproducibility of the device, and the sensitivity to the polarization When two waveguides are too close, the orientation of the neutral axis of each waveguide changes because of the stress modification due to the presence of the other one ([Visc. 90]) The variation is measured by the γ parameter The axis becomes again parallel and orthogonal to the surface when they are far enough (See Fig 8)

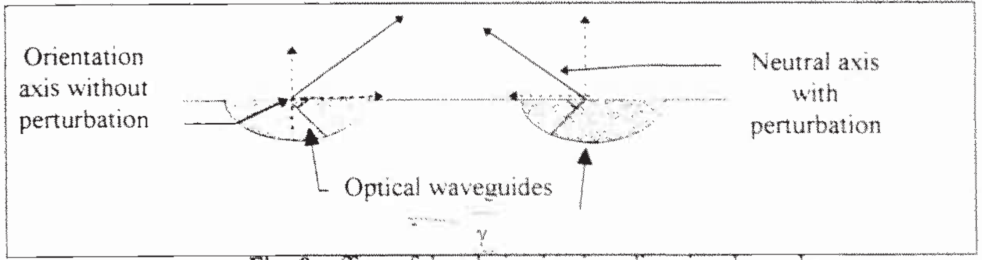

Fig. 8: effect of depolarization in a directional coupler

4.3 - Results analysis

Table 1 gives a comparison of the analyzed components The losses criterion is pondered by a factor 4, because of its high priority The criterion of feasibility are pondered by a factor 2 Polarization insensitivity is pondered by a factor 2 because of the requirements for visibility accuracy in interferometry. We do not search for a good reproducibility because it is not an industrial application even if it is quite important for the laboratory It is pondered by a factor 1 as for the wavelength insensitivity which is not essential as the photometric channels may compensate any chromatic effects Although the marks are little arbitrary, this table allows to point out some general trends of each solution

	Feasibility (F)	Reproducibility (R)	Wavelength insensitivity (W)	Polarization insensitivity (P)	Losses (L)	Mark
Y-junction	4	4	4	4	1	C
Hybrid coupler	3 *	3 *	4 *	4 *	4 *	A
X-coupler	3	3	3 *	3 *	3 *	B
Asymmetrical directional coupler	2 *	2 *	3	2	2	D
Symmetrical directional coupler	2	2	2*	2*	2*	E

*: *has not yet been verified experimentally, so it's a temporary mark.*

Table 1: comparative table between the structures

Because of difficulties of making, the directional couplers are not well marked. The hybrid coupler presents a good trade-off. The X-coupler is nearly as good as the hybrid couplers, but it presents few radiative losses. Note that the Y-junction would be very good if it did not loose so much energy.

5 - COUPLER SIMULATION

First, the structure modeling needs the reduction of a 3 dimensional problem in a 2D analysis. This step is achieved thanks to the Effective Index Method [Marc. 74]. The 3D waveguides is decomposed in two planar guides (Fig 9): the first is asymmetrical in the vertical direction. From the resolution of the dispersion equation of such a structure, the depth effective index ne_1 is deduced. The second one is symmetrical with a guide index equal to ne1. Thanks to the dispersion equation for a symmetrical guide, the effective index of propagation ne_2 of the mode in the confined guide is deduced.

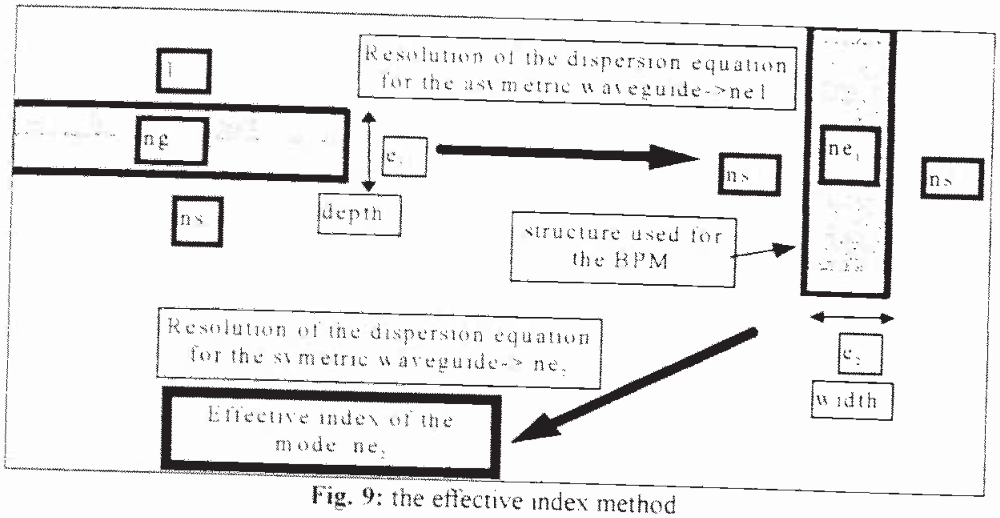

Fig. 9: the effective index method

The symmetrical structure obtained after the first step reduction is used with the Beam Propagation Method [Flec. 91]. This method allows to know the variation of the mode shape along the propagation, and so the losses and the energy repartition between the ouput guides. As the technological parameters are not well modelized, we define two figure functions depending on various parameters (wavelength, polarization, technology) $\Delta n_{eff} = \mathbf{n_s - ne_1}$, and the width $\mathbf{e_2}$ of the waveguide which depends only on the technological parameters.

By varying these functions and observing the intensity repartition at the ouput, we are able to know the behavior of the structure when the wavelength or the polarization changes. This method will be used for all the structures, except for the directional couplers whose spectral behavior is analytically described. The simulation of a symmetrical X-coupler with an angle of 0.5° and a phase difference between the inputs equal to 0° or 180° is given in figure 10. Measurements must be done to verify the simulation results and to optimize the bandwidth of the waveguides thanks to a spectral analyser. Moreover, a better knowledge of the technological parameters is expected.

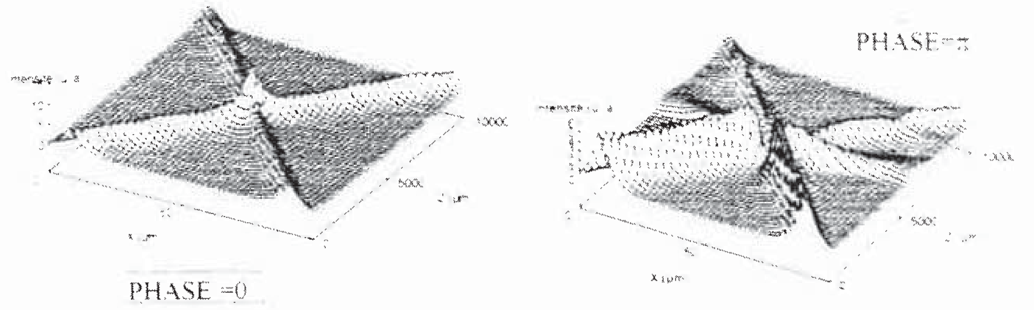

Fig. 10: simulation of X-couplers we observe the losses at the intersection when the beams are in opposition of phase on the right figure

6 - CONCLUSION

This article shows that the losses in the component based on Y-junction can be removed by an other four-ports structure keeping all the information. Different devices have been compared on the criteria of feasibility, reproducibility, wavelength and polarization insensitivity and losses. The study concludes that in a first time, the hybrid coupler and the X-coupler must be simulated via a EIM+BPM method and then made. Complementary measurements of their bandwidth may be realized with a spectral analyser to verify the broad-band single-mode ability, necessary for analyzing astronomical observation (young stars, active galactic nuclei and exoplanet research).

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7 - REFERENCES

[Kern, 96] P. Kern and F.Malbet, *Integrated optics for astronomy interferometry*, 1996

[Kern, 97] this volume

[Berg, 97] this volume

[Marc, 74] D Marcuse, *Theory of dielectric optical waveguides*, Academic press, 1974

[Scha, 92] I. Schanen Duport, *Etude de structures collimatrices en optique intégrée sur verre, application à l'interferometrie*, These de l'Institut National Polytechnique de Grenoble, 1992

[Izut, 82] M Izutsu, *Operation mechanism of the single-mode optical-waveguide Y-junction*, Optics Letters, Vol 7, No 3, 1982

[Agr, 87] N.Agrawal, L. McCaughan and S.R. Seshadri, *A multiple scattering interaction analysis of intersection waveguides*, J.Applied Physics, Vol 62, No 6, Sept 1987.

[Ger, 94]. P Gerard, *Methode modale pour l'etude de dispositifs d'optique intégree sur verre*. These de l'Institut National Polytechnique de Grenoble, 1994

[Izut, 82] M.Izutsu, A.Enokihara, and T Sueta, *Optical-waveguide hybrid coupler*, Optics Letters, Vol 7, No 11, Nov 1982

[Huss, 90] C P. Hussel, R V Ramaswamy, R Srivastava, and J.L. Jackel, *Wavelength and polarization insensitive 3 dB cross-coupler power dividers by ion exchange in glass*, Applied Physics Letter, Vol 56, No 24, june 1990

[Yana, 90] H Yanagawa, S Nakamura, I Ohyama and K Ueki, *Broad-band high-silica optical waveguide star coupler with asymmetric directional couplers*, IEEE Journal of lightwave technology, Vol 8, No 9, sept 1990

[Taka, 89] A.Takagi, K.Jinguji, M.Kawachi, *Broadband silica-based optical waveguide coupler with asymmetric structure*, Electronics Letters, Vol 26, No 2, (Jan 1989)

[Visc, 90]. C.Visconti, *Etude de la birefringence dans des guides optiques fabriques par echange d'ions sur substrat de verre: separateur de polarisation*, These de l'Institut National Polytechnique de Grenoble, 1990

[Flec, 91]. J.A Fleck, Jr., *Helmholtz beam propagation by the method of Lanczos reduction*, SPIE Vol 1583, Integrated Optical Circuits, 1991.