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# OPTICAL COMPONENT MODELING AND CIRCUIT SIMULATION USING SERENADE SUITE

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## ABSTRACT

This communication introduces the modelling of optical and optoelectronic components and the simulation of optical circuits and links using SERENADE Suite. A specific library describing several optical components and devices has been established and integrated as User-Defined-Models into the SERENADE Suite. Then, the simulation facilities of SERENADE are used to study some integrated optical circuits and fiber links.

## INTRODUCTION

The optical technologies based on the use of optical fibers and integrated optic/optoelectronic devices is a fast growing field. In the last decade several theoretical and technological advances have been accomplished and allow today very sophisticated applications both for ultra large bandwidth transmission and the processing of high speed signals. Nowadays, the technology allows more and more complex applications using a large number of components integrated on the same substrate or connected by optical fibers.

At the origin, the optical fibers have been used for the long distance transmission thanks to their large band width and low loss properties. The transmitted signals was simply intensity modulated lasers and direct envelope detection was used for the regeneration and the reception. To achieve such a solution the engineers have to optimise a limited number of independent parameters. Today, multiplexed architectures TDM, WDM and DWDM have replaced the original simple transmission [1]. The large architecture of the transmission networks includes large number of new elements: optical multiplexers and demultiplexers, optical amplifiers, optical filters, add/drop elements, etc... Due to this complexity, the number of parameters to be optimised by the designers become large, and generally, they are not independent.

Concerning the integrated devices, they was developed at the origin to be compatible with optical fibers in order to replace classical optical elements. The technological advances allow today the design and the realization of full optical function on the same substrate.

So, for both optical links and integrated optical circuits, design and simulation tools are needed in order to improve the characteristics, to optimise the performances and more generally to simplify the design and the realization of optical applications.

## MODELLING PRINCIPLE

In both previous cases, we deal with a group of components interconnected with waveguides propagating electromagnetic signals. It is important to notice that many optical components have their analogue in the microwave domain. In fact, optical and microwave elements are designed on the same principle: controlling guided propagated signals. Many engineers with a background in microwave technology entering the field of optics regard optical network as an "extension" of microwave networks, both technologically and theoretically. However, the difference between these two categories of components manifests itself on the network theory level. The common "single-mode" optical waveguides becomes bi-modes in optical component. The two propagating modes are nearly degenerate and differ mainly by their polarization.

In optical domain, the combination of polarization is described as the state of the polarization of the field. Most optical components are sensitive to the state of the polarization, and, therefore, a full account of its evolution is essential in optical network analyses. It is possible to represent an optical signal with a two-component vector known as the *Jones vector*. The later leads to a corresponding representation of optical components using *Jones matrices* [2]. The Jones calculus is very convenient for the study of guided-wave optical systems. In the analysis of such systems we are not concerned usually with the field distribution in the plane transverse to the direction of the waveguide, instead of it, we focus our attention on the field evolution in the propagation direction. The Jones calculus is an elegant way to eliminate the transverse field distributions from the analysis.

Concepts similar to the Jones vector are also used in the theory of microwave networks. In such situation, the microwave components are represented by their scattering parameters which lead to the S-matrix. The application of S-matrix to optics is not common until recently. In fact the use of S-matrix description in optics is somewhat problematic because the optical components are usually sensitive to variations in external conditions, such as temperature and pressure. In spite of these practical difficulties, the S-matrix concepts is very convenient for the theoretical analysis of optical networks.

The optical S-matrix differs from the familiar microwave S-matrix in that the matrix “elements” of the optical S-matrix are 2\*2 matrices themselves, to account for the polarization. Thus, the optical scattering parameters are 2\*2 matrices. In a proper context, these matrices may be regarded as transfer, or Jones, matrices.

In previous works the authors considered the S-matrix to analyse the microwave response of all-optical networks [3], and in a second paper a first attempt to use SERENADE Suite to simulate and integrated optical filter [4] has been made by the authors. Today’s paper is more general and introduces a global approach for the CAD of guided-wave optical circuits thanks to facilities offered by SERENADE Suite.

## MODELLING TECHNIQUE

Let us consider the simple case of a single-port component. The component is linear and time independent, and then, in the frequency domain the input and the output Jones vectors A and B are related by a linear set of equations:

$$[B_j] = [S_{ij}] * [A_i] + [C_j] \quad (1)$$

Where, for a n-port device, S is a complex 2n\*2n matrix and C is a complex 2n element vector, both independent of A. The matrix S is called the S-matrix of the component. We may also regard S as the Jones matrix of the component and C as an optical field source that may be present in the component. C has a significant value only in active component, such as optical sources or optical amplifiers. In passive components, C is normally neglected. The elements of the S-matrix are not independent. Two general physical principles impose certain relations between them. These principles are energy conservation and reciprocity. From the energy conservation principle it follows that the total power emerging from a passive component cannot exceed the total power emerging from a passive component cannot exceed the total power that is fed into it. The output power is always smaller than the input power because in practice all the components have some insertion losses. However, it is often convenient to consider an idealization, in which the losses are neglected and the output power is exactly equal to the input power-preserving component is unitary. The reciprocity principle stems from certain symmetry properties of the Maxwell equations with respect to time reversal. This symmetry is destroyed in the presence of magnetic interactions or by the Sagnac effect. The S-matrix of a reciprocal component is symmetric.

In SERENADE, we can create component by developing a description file: .dll using a C source file in Visual C++. In this file, we use some specific SERENADE ’s functions. So, for the description of a new component we give the Y-matrix of it (admittance matrix). For doing this, we must convert the S-matrix to Y-matrix. The relation linking these two matrices is:

$$[Y] = \frac{1}{Z_0} * \frac{[U] - [S]}{[U] + [S]} \quad (2)$$

Where [U] is the identity matrix, and Z<sub>0</sub> is the reference or the characteristic impedance. In case of different characteristic impedance at the access, the previous expression must be extended.

## EXAMPLES OF MODELS

Several ideal passive component have been developed. We will describe some of these models for illustrate the method. We will give the case of optical waveguide, and directional coupler.

## Perfect Waveguide

A waveguide is a two-port passive component. So  $C=0$  and  $B=S^*A$ . Ideally, these channels should be lossless and without reflections. Thus, the S-matrix of a perfect waveguide is unitary and symmetric (reciprocal). It has the following form:

$$S = \begin{pmatrix} 0 & F \\ F^T & 0 \end{pmatrix} \quad (3)$$

where  $F$  is unitary and  $0$  stands a  $2 \times 2$  null matrix.  $F$  has the following form:

$$F = \begin{pmatrix} \exp(j\phi_x) & 0 \\ 0 & \exp(j\phi_y) \end{pmatrix} \quad (4)$$

with:  $\phi_x = \frac{2\pi \cdot L \cdot n_x \cdot \nu}{c}$  and  $\phi_y = \frac{2\pi \cdot L \cdot n_y \cdot \nu}{c}$  (5-6)

where  $L$  is the waveguide length,  $n$  is the effective refractive index, and  $\nu$  is the optical field frequency.

The associated diagram is:

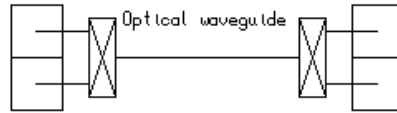


Fig. 1. Schematic representation of waveguide

The S parameter can be modified to include losses and dispersion. The optical fiber model is an extension of the waveguide one.

## Directional Coupler

A directional coupler is a four-port passive component. So  $C=0$  and  $B=S^*A$ . It plays an important role in optical networks. A perfect directional coupler conserves the power and does not reverse the signal flow. In other words, all the incoming signals injected into ports 1 or 2 are routed to ports 3 or 4, and vice versa. The S-matrix of an ideal and reciprocal directional coupler has the following form:

$$S = \begin{pmatrix} 0 & 0 & A & B \\ 0 & 0 & B & A \\ A & B & 0 & 0 \\ B & A & 0 & 0 \end{pmatrix} \quad (7)$$

Where  $A = \begin{pmatrix} \sqrt{1-K_x} & 0 \\ 0 & \sqrt{1-K_y} \end{pmatrix}$  and  $B = \begin{pmatrix} j\sqrt{K_x} & 0 \\ 0 & j\sqrt{K_y} \end{pmatrix}$  (8-9)

where  $K_x$  and  $K_y$  are the coupling factors between the two polarizations.

The associated diagram is:

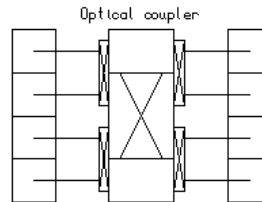


Fig. 2. Schematic representation of directional coupler

## SIMULATION EXAMPLE

Once the models are described into SERENADE, we can simulate any circuits based on these components. As an important example let us consider the Mach-Zehnder interferometer. It's representation under SERENADE environment is given on figure 3. It's an unbalanced Mach-Zehnder can be used as filter.

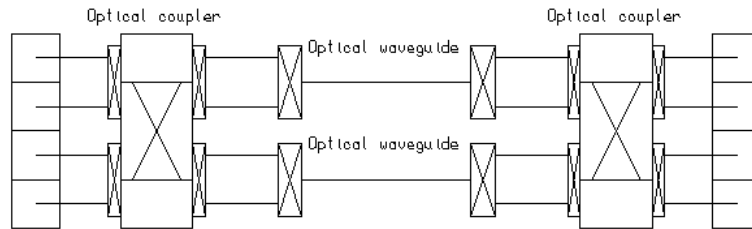


Fig. 3. A Mach-Zehnder representation under Serenade environment

After the linear simulation using SERENADE functions, we obtain the response of the circuit. The obtained results are given figure 4. These are the magnitude in the band 0.5-1 THz. We obtain the following results:

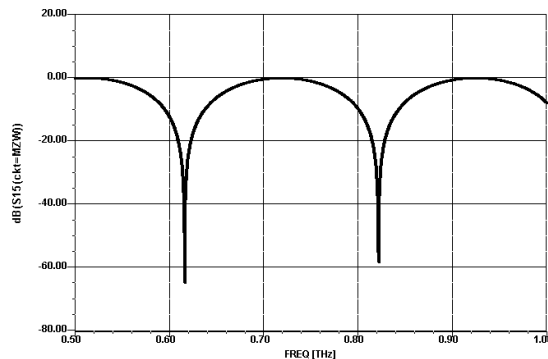


Fig. 4. A Mach-Zehnder interferometer frequency response

One notices that the simulated results are fully in agreement with the theoretical predictions and then confirm our general procedure.

## CONCLUSION

In this study, we introduced the simulation of optics and optoelectronics devices and circuits thanks to the facilities available in the SERENADE Suite. Some optical components have been introduced as User-Defined-Models into SERENADE. Then some of them have been used to define an all optical circuit, i.e. Mach-Zehnder interferometer. A linear simulation of such a circuit has been accomplished and the obtained results are confirmed by the experimental measures. This validate our general procedure and confirm the applicability of SERENADE to the CAD of optical and optoelectronic circuits. The next steps of this development will concern the modelling of the other optical component and their introduction into SERENADE environment.

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