Design on tolerances in integrated optics

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Abstract. *The aim of the "design on tolerances" technique is to design a circuit that is robust against statistical variations of the parameters due to technological processes and aging, maximize the yield and locate the most critical parameters of the circuit. Preliminary numerical examples concerning integrated optical filters are discussed.*

Introduction

The scenario of optical interconnects, optical networks and wideband connections will shortly require large and complex optical circuits, probably based on integrated planar technologies, but exploiting hybrid integration to combine a large number of functions towards a VLSI level (Very Large Scale of Integration, a well known concept in electronics). It will be then of major importance the availability of software platforms able to simulate and design complex and large circuits, in order to reduce design, production and packaging costs and increase the yield and the reliability of the devices.
The design of a circuit is typically carried out by searching the circuit parameters values that satisfy a given spectral transfer function or a time response in very well specified conditions. The designer operates by using synthesis techniques, optimization procedures and his own experience. However, the set of nominal values corresponds to a single point in the multi-dimensional space of the circuit variables, moving within a domain whose boundaries are fixed by technological tolerances, the uncertainty of the parameters and the drift due to aging or other phenomena. For these reasons, an even more important aspect in the design procedure is the possibility to access more sophisticated calculations such as optimizations, sensitivity analysis, yield estimation, risk analysis and concepts as 'statistical design' or 'design on tolerances'.
In this contribution it is not possible to be exhaustive on this subject but an initial investigation is carried out. The idea, quite well known in many other fields such as electronics and microwave, is to modify the parameters of the circuits obtained with classical 'deterministic' design techniques to get a more robust or 'optimal' set of parameters of the circuit. The technique is briefly described and some results concerning the yield and the sensitivity obtained on two filters with different architectures and similar spectral responses are discussed.

Yield and sensitivity

Let's define a measure of the characteristics or performances of a circuit, called "circuit performance space" and a space defined by all the variables and parameters that have some role in determining the circuit behavior. The circuit requirements requested in the circuit performance space define an acceptability region R_A in the space of variables, in which the values assumed by the circuit variables satisfy such specifications. If the region R_T in the variable space identified by processes tolerances (for example) around the nominal values of the variables is not completely included in the acceptability region, some circuits will not satisfy the requirements defined in the performance space.

This typically happens in mass production processes. The yield is related to such overlap, that is as the ratio between the number of circuits satisfying specifications and the total number of produced circuits [1, 2] or, equivalently, as the probability to generate a circuit satisfying the specifications. Said $f(\phi)$ the joint probability density distribution of the circuit variables, the yield is given by [2]

$$Y = \int_{R_A} f(\phi)d\phi = \int_{-\infty}^{+\infty} I_A(\phi)f(\phi)d\phi = E\{I_A(\phi)\} \tag{1}$$

where I_A defines the acceptability region R_A. The yield is therefore the average value of the acceptability function in the whole variables space. The integral in (1) can be estimated with the Monte-Carlo method, by generating N circuit parameters sets ϕ_k, ($k=1...N$) according to $f(\phi)$ and estimating the integral (1).

The variance of the estimated yield decreases only as the square root of N and in order to reduce the Monte-Carlo estimator variance, we have chosen to modify the algorithm by introducing the correlation between successive estimations (correlated sampling). The information on the yield can be exploited to adjust the nominal design of the circuit variables by using a standard optimizer routine, or a more efficient algorithm for the specific yield optimization problem, such as the "gravity centers" algorithm [3,4] to find the "best" set of circuit parameters.

Fig. 1 shows schematically the concept for a simple case with only two parameters, P_1 and P_2. In a) the nominal design D_N ensure the 'best' circuit performance but the uncertainty on the parameters defines a space R_T with a poor overlap with the acceptability region, that is a low yield. In b) the parameters of the circuit have been moved to D_F with an evident increase of the yield.

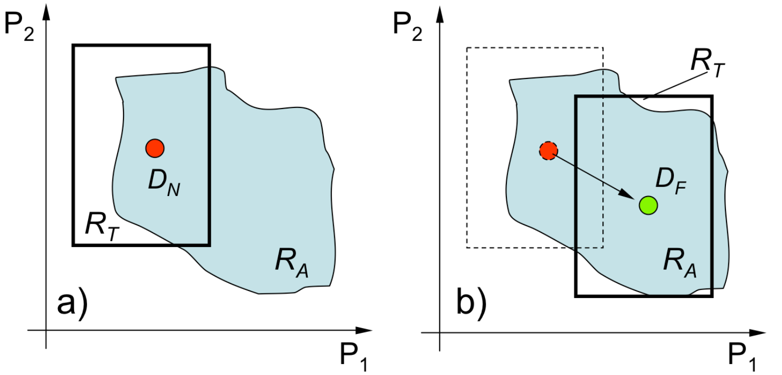

Fig. 1 – Yield maximization and design centering by using information on parameters tolerances.

The sensitivity parameter *M*

This analysis brings naturally to the definition of the parameter M, connected to the sensitivity of the yield with respect to each parameter of the circuit. The parameter M is based on the concept of statistic independence: for a variable x we call $p(x)$ the relative density of probability, $p_P(x)$ the conditioned probability to pass the specifications and $p_F(x)$ the conditioned probability to fail the specifications. The overlap degree of the two probability densities $p_P(x)$ and $p_F(x)$ is a direct measure of the weight of the variable on the yield of the circuit. M is evaluated by using a Monte-Carlo approach [5] as

$$M = \int_{-\infty}^{+\infty} \left| p_P(x) - p_F(x) \right| dx \, . \qquad (2)$$

The parameter (component) of the circuit with the smaller degree of overlap, that is with the largest M, is the greatest responsible for the deterioration of the yield. The parameter M can assume a value between 0, in case of no influence, and 2 in case of total mismatch between $p_P(x)$ and $p_F(x)$.

Optical Filter Comparison

In this section, as an example of "design on tolerances", a 7-cascaded Mach-Zehnder filter and a 4 coupled-ring-resonator filter are considered. The two different filter architectures are designed with classical techniques in order to respect the same spectral specifications. The number of stages has been found by maximizing the yield with respect to the number of stage in case of tolerances both on the coupling coefficients K of the directional couplers and on the effective refractive index n_{eff} of the waveguides. The FSR of the filters is 100GHz, the bandwidth is 20GHz and the minimum requirements in both passband and stopband are clearly marked in Fig. 2. The minimum off-band rejection is 18 dB and the in-band return loss is 15 dB.

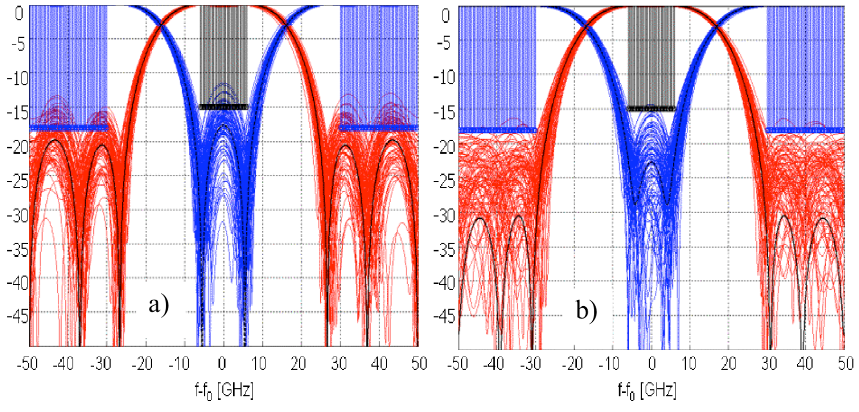

Fig. 2 - *Impact of the tolerances on a 7-cascaded Mach-Zehnder before a) and after b) yield optimization.*

Fig. 2a) shows the impact of the tolerances of the eight coupling coefficients {98.41; 0.76; 5.13; 41.99}% of the cascaded Mach-Zehnder symmetrical filter. In these conditions only the 24.5% of the realized circuits satisfy both in-band and off-band requirements. The probability distribution of the K coefficients has been assumed Gaussian with a standard deviation of the field coupling κL equal to 1 degree. A Gaussian statistic of the local effective refractive index with a standard deviation equal to $\sigma_{neff} = 5 \cdot 10^{-6}$ has been assumed. By means of an optimization technique, the new coupling coefficients {99.36; 0.87; 4.15; 43.20}% are calculated. Fig. 2b) shows the transfer function of 100 realizations on the optimized filter design and the yield now is greater than 90%. It is interesting to note that such a design is more critical compared with the nominal one as can be seen by the wider spread of the spectral responses but the final yield is much higher. In general it is difficult to say 'a priori' which is the 'best' design and a 'yield optimizer' is the only tool to perform such a process.

Similar results are found for the cascaded coupled-ring architecture, not shown for brevity. In this case the yield increases from 89.3% to 92.4% and the coupling coefficients move from D_N={83.09; 34.92; 20.97; 34.92; 83.09}% to D_F={83.29; 34.7; 21.26; 34.7; 83.29}%. Note that despite the very high yield of the nominal design, a small improvement in the yield is found as well with a very small adjustments of the parameters. This does not means that the coupling coefficient should be realized with such a precision but that the design must centered in D_F, a substantial difference.
An even more important information derives from the sensitivity analysis of the various parameters of the circuits. Fig. 3 shows the parameter *M* relative to the parameters of the coupled-ring filter. In the figure it is clearly visible that the parameter *M* of the couplers decreases with the standard deviation of the n_{eff}. This means that if the control on the refractive index is very tight, the couplers, and especially the central couplers, are the most critical components of the circuit. The parameters *M* related to the refractive index of the rings, instead, increase with respect to σ_{neff}. Note that the refractive index of the first rings is almost non-influent. The curves cross near the standard deviation σ_{neff}=5e-6. Before this value the most critical components are the directional couplers, while for higher values it is the refractive index that is responsible of a decrease of the yield.

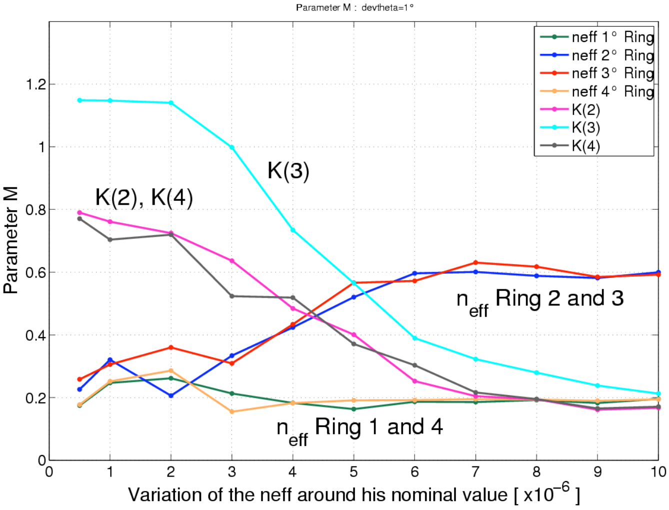

Fig. 3 – 4-cascaded ring filter. Parameter M of the central couplers and of the refractive index of the rings versus the standard deviation of the refractive index.

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