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General Modeling, Fabrication & Measurement Report

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Title	On the Faby-Pérot fringes in transmission and insertion loss measurements
Summary	This report discusses and quantifies the detrimental effects of Fabry-Pérot resonances that appear when transmission measurements are done on chips that have uncoated facets. The hypothesis until now was that a spectral average over multiple fringes would be a valid approach. This report quantifies the effect.
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On the Faby-Pérot fringes in transmission and insertion loss measurements

This report discusses and quantifies the detrimental effects of Fabry-Pérot (FP) resonances that appear when transmission measurements are done on chips that have uncoated (as-cleaved) facets. The hypothesis until now was that a spectral average over multiple fringes would be a valid approach. This report quantifies the effect.

1 Rationale

An often-used technique for measuring component losses is to subtract from the transmission loss of the device under test the loss of a reference waveguide. As-cleaved the facets give reflections which lead to FP resonances. Anti-reflection coating can be used to suppress these reflections, but these require an extra process step. Also angled facets can be used, but these can easily lead to higher-order mode excitation. So in practice measurements are often done with as-cleaved facets.
The question is then whether this approach is still valid in the presence of FP resonances. The common approach is to average these out by wide-band measurements, spanning multiple fringes. Obviously narrow-band measurements, less than a fringe wide, can never be done on such samples, since these would lead to arbitrary loss values.

2 Theory

The transmission of light through a FP-cavity, e.g. an optical waveguide with facets, is described by the following equation [1]:

(1.1) $$P_{out}(\lambda) = \frac{(1-R_1)(1-R_2)e^{-\alpha L}}{\left(1-\sqrt{R_1R_2}e^{-\alpha L}\right)^2 + 4\sqrt{R_1R_2}e^{-\alpha L}\sin^2\left(\frac{2\pi n_{eff}(\lambda)L}{\lambda}\right)} P_{in}(\lambda) \ .$$

In here $P_{in}(\lambda)$ and $P_{out}(\lambda)$ are the input and output optical power respectively as a function of free-space wavelength λ, R_1 and R_2 are the facet power reflections, α is the optical power propagation loss in units of [m^{-1}] [1], L is the cavity length, and $n_{eff}(\lambda)$ is the effective index of the waveguide, dependent on the wavelength. Throughout this report losses are defined with a positive value (negative meaning gain). Using $R_1 = R_2 = R$ and $\lambda = 2\pi c/\omega$, the transfer function can be written as:

(1.2) $$H(\omega, R, \alpha) = \frac{(1-R)^2 e^{-\alpha L}}{\left(1-Re^{-\alpha L}\right)^2 + 4Re^{-\alpha L}\sin^2\left(\omega\frac{n_{eff}(\omega)L}{c}\right)} \ .$$

[1] Losses are assumed to be independent of wavelength.

This equation is implemented and analyzed using the MathCad (v14) software package. A typical example, representative of a FP transmission of a 1-mm silicon waveguide, is shown in Fig. 1. The free-spectral range can be calculated by (1.3). Substituting the effective index $n_{eff}(\omega)$ with the group index $n_g = n(\omega) + \omega \cdot dn/d\omega$ leads to (1.4). This results in a free-spectral range (FSR) of 42.9 GHz (= 0.34 nm), which is as expected for the given parameters.

(1.3)
$$(\omega+\omega_{FSR})\frac{n_{eff}(\omega+\omega_{FSR})L}{c}-\omega\frac{n_{eff}(\omega)L}{c}=\pi$$

(1.4)
$$\omega_{FSR}=\frac{\pi c}{n_g L}=2\pi f_{FSR}$$

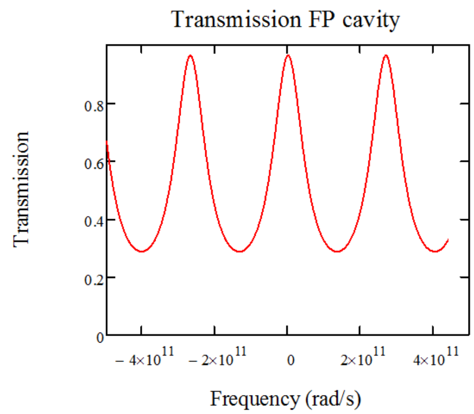

Fig. 1 FP transmission for $R = 0.3$, $\alpha = 20\ \mathrm{m}^{-1}$ (~0.9 dB/cm), $n_g = 3.5$ and $L = 1$ mm.

When broadband light is injected, the power detected by a photodetector is the integration over the spectrum of $H(\omega,R,\alpha)$. The same holds true when a spectrally resolved measurement is done but results are averaged afterwards. The detected spectral power density $P_{det}(R,\alpha)$ [$\mathrm{Wrad^{-1}s}$] for a spectrally flat input power density P_{in} [$\mathrm{Wrad^{-1}s}$] can be described as follows, integrating over one FSR, i.e. one fringe:

$$H_{\mathrm{int}}(\omega,R,\alpha)=\int\frac{A}{B+C\sin^2(D\omega)}d\omega=\frac{A\cdot\mathrm{atan}\left(\frac{\tan(D\omega)\cdot\sqrt{B+C}}{\sqrt{B}}\right)}{\sqrt{B}\cdot D\cdot\sqrt{B+C}}+Const$$

(1.5)
$$A=(1-R)^2e^{-\alpha L}$$
$$B=\left(1-Re^{-\alpha L}\right)^2$$
$$C=4Re^{-\alpha L}$$
$$D=\frac{n_{eff}L}{c}$$

(1.6)
$$P_{\text{det}}(R,\alpha)=\frac{H_{\text{int}}\left(\frac{\omega_{FSR}}{2},R,\alpha\right)-H_{\text{int}}\left(-\frac{\omega_{FSR}}{2},R,\alpha\right)}{\omega_{FSR}}P_{in}$$

For the parameters in Fig. 1 this leads to a detected power density of $0.526\cdot P_{\text{in}}$ [Wrad^{-1}s]. A numerical averaging of (1.2) over the same interval was done to verify the equation and leads to the same result. As can be seen, the value of the detected power does not scale linearly with the reflection, R, and the loss, exp(-αL), which means that care should be taken with the interpretation of the results of various common experiments, as described in the next section.

3 Application

A typical measurement is the insertion loss measurement, where the transmission of a reference waveguide is subtracted from the waveguide that contains the component of interest, as schematically shown in Fig. 2. This can, e.g., be an AWG, an MMI or just a longer (lossy) waveguide. This approach eliminates coupling losses and setup related losses. Moreover sources that are not spectrally flat, e.g. an SLED or Erbium-based ASE source, can be normalized like this. Underlying this approach is the assumption that the difference in loss will be the insertion loss of the component of interest, as the reference waveguide loss is generally low in comparison. The question is whether this is still true in the presence of strong facet reflections.

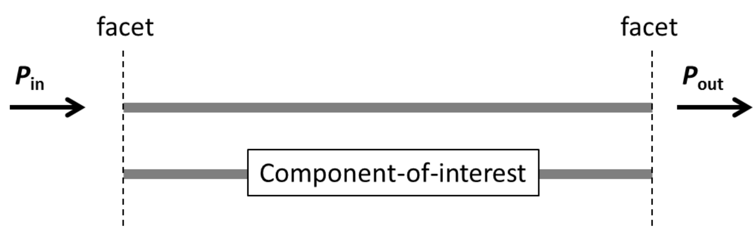

Fig. 2 Schematic overview of the case. Light is coupled in using a lensed fiber or microscope objective. The reference waveguide is shown at the top and the component that is to be measured is shown on the bottom.

We define $\alpha_{\text{tot,ref}}$ and $\alpha_{\text{tot,comp}}$ as the total loss between the facets for the reference waveguide and the waveguide containing the component of interest respectively, expressed in [dB] (Fig. 2). The loss of the component of interest is ($\alpha_{\text{tot,comp}}$ - $\alpha_{\text{tot,ref}}$). The measured loss is, however:

(1.7)
$$Loss\left(R,\alpha_{tot,ref},\alpha_{tot,comp}\right)=-10\log\left[\frac{P_{\text{det}}\left(R,\ln\left(10^{0.1\cdot\alpha_{tot,comp}}\right)L^{-1}\right)}{P_{\text{det}}\left(R,\ln\left(10^{0.1\cdot\alpha_{tot,ref}}\right)\cdot L^{-1}\right)}\right]$$

The difference in measured loss and actual loss can then be expressed by:

(1.8)
$$Error\left(R,\alpha_{tot,comp},\alpha_{tot,ref}\right)=Loss\left(R,\alpha_{tot,comp},\alpha_{tot,ref}\right)-\left(\alpha_{tot,comp}-\alpha_{tot,ref}\right)$$

The results of this analysis are shown in Fig. 3. The error as expressed by (1.8) (in units of dB, i.e. the absolute error in the component loss measurement) is plotted as a function of the actual component loss. Results for four different values for the facet reflection are shown. Obviously there is no error for zero reflection, since FP-effects are not present in this case. For realistic values of the reflection[2] (0.2 – 0.4) the error can be significant, especially for the lower component loss values, with up to 30% overestimation of the loss, e.g., 0.28 dB error on a 1-dB component loss value for $R = 0.4$. Please note that this analysis is valid for a single transverse mode. Ripples in the spectrum that are caused by multiple transverse modes would require a completely different analysis.

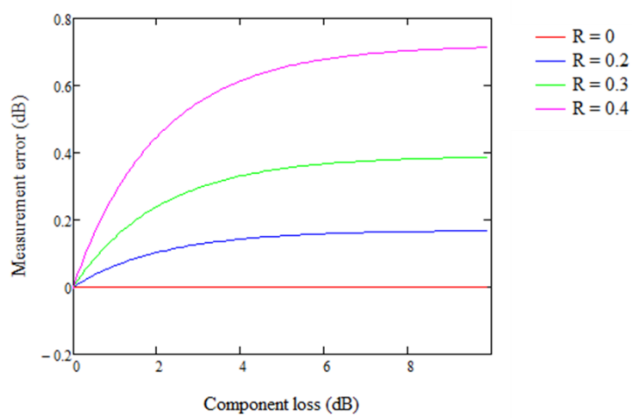

Fig. 3 Calculated error between the measured and actual loss for a component in a waveguide with a loss of 1 dB/cm and a length of 1 mm. The reference waveguide has the same values.

4 Conclusion and recommendations

It is clear that when accurate insertion loss measurements have to be done, the FP effects have to be taken into account when no AR coating is used. Data can be corrected for this effect, as the theory is straightforward.

In the case of multiple cavity reflections and/or cavities, such as in the case of 2×2 MMIs, the FP equations become more complex. Analysis of this effect is beyond the scope of this short report. The presented results indicate, however, that such an analysis would be required when such measurements are to be done.

5 References

1 F.M. Soares, "Photonic Integrated True-Time-Delay Beamformers in InP Technology," PhD thesis, Technische Universiteit Eindhoven, 2006

[2] Note that waveguide facet reflections require a different calculation than a mere Fresnel-reflection approach, which is valid for plane waves. Reflections of 0.2 – 0.4 are realistic for silicon photonics.