Technical University of Denmark

DTU

High precision planar waveguide propagation loss measurement technique using a Fabry-Perot cavity

Feuchter, Thomas; Thirstrup, Carsten

[Link back to DTU Orbit]

DTU Library
Technical Information Center of Denmark

High Precision Planar Waveguide Propagation Loss Measurement Technique Using a Fabry-Perot Cavity

Thomas Feuchter and Carsten Thirstrup

Abstract— A high precision measurement technique for characterizing the propagation loss in silica low-loss optical waveguides, based on measuring the contrast of a Fabry-Perot cavity, is demonstrated. The cavity consists of the waveguide coupled to two polarization-maintaining fibers, each end facet coated with dielectric mirrors, leaving the reflectivity as an adjustable parameter. The contrast is measured by modulating the cavity length without influence on the waveguide characteristics and the coupling efficiency. A double modulation of the cavity length reduces the measurement uncertainty, and provides a measurement precision better than 0.1 dB, corresponding to 0.02 dB/cm in case of a 5 cm long waveguide.
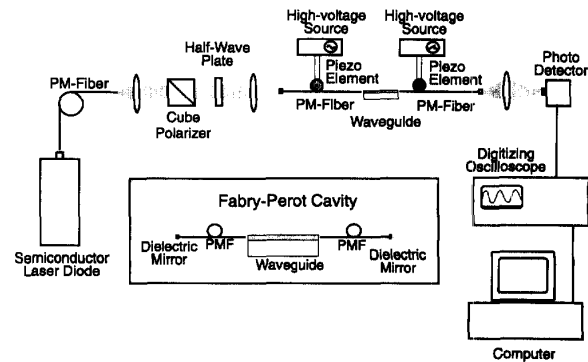

Fig. 1. Schematic view of the experimental setup for Fabry-Perot cavity waveguide loss measurements. Insert shows the detailed cavity configuration consisting of the waveguide coupled to two polarization maintaining fibers.

I. INTRODUCTION

FOR some years now, it has been possible to fabricate planar dielectric waveguides with low propagation losses in optical materials by various techniques. Special attention has been paid to devices optimized for interconnection with optical fibers for communication and sensing purposes, which in many cases require low optical losses (< 0.1 dB/cm) in order to maintain the signal-to-noise ratio. Such waveguides can be the backbone of future integrated optics, and many applications have already been demonstrated [1].

One of the main problems of characterizing optical waveguides with low losses is to perform an accurate measurement of the propagation loss, since a planar waveguide often is short (typically shorter than 5 cm) compared to optical fibers, leading to a total propagation loss below 0.5 dB, which is comparable to coupling and Fresnel losses. Several measuring techniques have been proposed such as the cut-back method [2], the prism coupling method [3], the scattered light measurement method [4], the photothermal deflection method [5], the internal modulation method [6] and the Fabry-Perot interferometer method [7]-[8]. The first four methods are well suited for characterizing waveguides with losses larger than 1dB/cm as they normally exhibit large uncertainties. The methods described in [7]-[8] are based on measurements of the contrast of a Fabry-Perot cavity consisting of an optical waveguide with reflections from the end facets, which are advantageous for low-loss waveguides (< 1dB/cm). In the technique described here a similar approach is employed, but in this case the cavity is extended by two optical fibers, each with a dielectric coated mirror on one end of the fiber and the

other end coupled to the waveguide as shown in Fig. 1. The performance of the measurement is improved by this technique as the mirror reflectivity is an adjustable parameter, which can be optimized for high precision.

II. THE MEASUREMENT TECHNIQUE

The coherent intensity transmission of a Fabry-Perot cavity as depicted in the insert of Fig. 1 is determined by the following equation:

$$\frac{I_t}{I_0} = \frac{\eta T^2 \exp(-\alpha)}{(1 - R\exp(-\alpha))^2 + 4R\exp(-\alpha)\sin^2(\frac{\phi}{2})} \quad (1)$$

$R = \sqrt{R_1 R_2}$ and $T = \sqrt{T_1 T_2}$, where $R_{1,2}$ and $T_{1,2}$ are the intensity reflection and transmission coefficients for the two dielectric mirrors. α is the total intensity attenuation from mirror to mirror, and $\phi = 2\beta L$ is the phase delay, L being the cavity length and β being the propagation constant in the waveguides. η is the coupling efficiency to and from the cavity.

By changing the length of one of the fibers in Fig. 1, either by heating a section of the fiber or by stretching it using a piezo-electric element, the optical length of the cavity is changed and the transmission exhibits Fabry-Perot fringes with maxima and minima as predicted by (1). From the maximum and minimum transmitted intensity, I_{max} and I_{min}, the contrast K is defined:

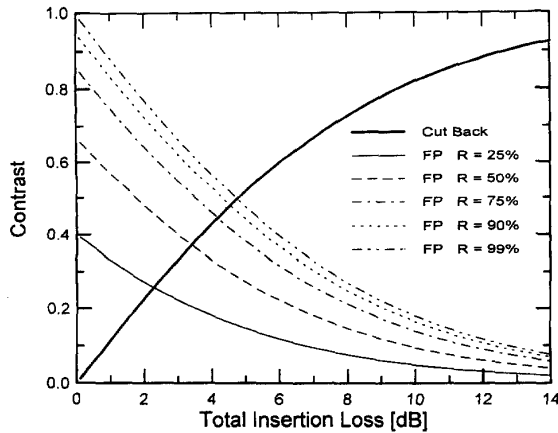$$K = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad (2)$$

Fig. 2. Calculated contrast of the Fabry-Perot cavity and the contrast obtained from the cut back method versus total insertion loss; the fiber mirror reflectivity R is a parameter.

and $R \cdot exp(-\alpha)$ can be expressed as a function of K;

$$R \exp(-\alpha) = \frac{1}{K}\left(1 - \sqrt{1 - K^2}\right) \quad . \quad (3)$$

The effective mirror reflectivity, R, can be determined by measuring the contrast of the cavity consisting of the two fibers only. The propagation losses of the fibers included in the characterization of R are several orders of magnitude smaller than the waveguide losses and can be neglected.

The total cavity loss α is dominated by the waveguide insertion loss which consists of the input and output coupling losses and the propagation loss. In order to separate these contributions, the waveguide is cleaved after an initial measurement, and the insertion loss of each section is measured. Assuming identical coupling efficiencies, the coupling loss and the propagation loss can be isolated using (4a) and (4b).

$$\alpha_{coupling} = \alpha_a + \alpha_b - \alpha_{total} \quad (4a)$$

$$\alpha_{prop} = 2\,\alpha_{total} - \alpha_a - \alpha_b \quad (4b)$$

where α_{total}, α_a and α_b are the insertion loss of the total waveguide and each of the two sections and α_{prop} and $\alpha_{coupling}$ are the propagation losses and total coupling losses, respectively.

The main advantage of using the Fabry-Perot measurement technique becomes clear when the contrast is evaluated. In Fig. 2, calculations of the contrast obtained from (1) and (2) are shown as a function of the total insertion loss for different values of the mirror intensity reflection coefficient. For comparison the corresponding contrast is shown for the cut-back method, defined here as for the Fabry-Perot cavity with I_{min} and I_{max} being the signal level before and after the cut-back, respectively. Generally, the method described here is advantageous compared to the cut-back method for insertion losses lower than app. 4 dB, when a sufficiently high mirror reflectivity is employed. From Fig. 2 it is also clear that the resolution of the measurement increases with reflectivity. For uncoated silica waveguides and fibers the intensity reflectivity is approximately 4%, which will cause a poor contrast.

The experimental setup is shown schematically in Fig. 1. The light source was a Santec TSL-80 external cavity semiconductor laser with a narrow linewidth (coherence length > 300 m). It was operated at 1.55 μm with a constant output power of approximately 0.1 mW. The output beam was collimated, linearly polarized using a cube polarizer, and the polarization was adjusted to match the polarization axis of the fibers by a λ/2-plate, before coupling into the cavity. Each of the two fibers was winded around a cylindrical piezo-electric element with a diameter of 12 mm and the cavity length was modulated by the two piezo-electric elements using 0 - 250 V sine and saw- tooth generators with 0.01 - 1000 Hz modulation frequency. During the measurements, one fiber was modulated fast (1000 Hz) while the other fiber was modulated with a slow (0.1 Hz) saw-tooth modulation. In order to reduce reflections at the fiber to waveguide interfaces, index matching oil was used. The intensity of the transmitted light was measured using a photodetector and monitored on a digitizing oscilloscope. From the oscilloscope, the data was transferred to a computer, which stored the data and performed the necessary calculations.

The precision of the measurement is limited by the following factors

* the repeatability of the coupling efficiency.
* the coherence length of the laser source.
* the control of the polarization.
* the level of intracavity reflections.

The coupling efficiency depends on the displacement, the angle deviation and mode mismatch at the interface between the fibers and the waveguide, and it is difficult to obtain the same coupling efficiency in independent measurements. By using positioning equipment with sub-micron precision, a repeatability better than 0.1 dB is obtained in the present experimental setup. The accuracy of the measurement is limited by this repeatability. However, it is expected that automated positioning will reduce this uncertainty, leading to more accurate results.

As the cavity length typically is 50 - 100 cm, it is necessary to use a light source with an appreciably long coherence length. If the coherence length is too short, the Fabry-Perot resonances cannot be resolved and the measurement will predict a higher insertion loss. In [9], the requirements on laser linewidth in Fabry-Perot based loss measurements of waveguides was evaluated, and showed the need for a very narrow linewidth source. The coherence length of the laser used in the current experiments was longer than 300 m, which is sufficient for resolving the interference fringes with a precision better than 1% (0.04 dB) for contrasts lower than 0.5 and cavity lengths shorter than 1 m. For the experimental setup these requirements were fulfilled.

It is necessary to use polarization maintaining fibers in the cavity. A change in polarization inside the cavity will lead to a situation with two coupled cavities, one for each polarization, and the fringes will be difficult or impossible to resolve. In order to make a polarization maintaining cavity, the polarization of the source must be aligned to match to the fiber polarization axes, and the axes of the fibers and the

waveguide must also be aligned. Furthermore, the waveguide must be polarization maintaining which usually is the case for planar waveguides.

The intracavity reflections arising at the interfaces between the fibers and the waveguide must be minimized. Numerical simulations and experimental results show that even reflections at levels below -30 dB can cause large variations in the measured contrast. The measured contrast is a function of the actual optical path length of each of the optical fibers and of the waveguide, and a change in these components by a fraction of a wavelength will change the measured contrast. Since the lengths will change slowly with temperature, the measured contrast will change accordingly. Numerical simulations show that for intracavity reflections lower than -20 dB the average value of the contrast measured for a large number of interference fringes is unaffected by internal reflections, when the cavity is subjected to a linear change in length. This remains valid for all relevant values of the mirror reflectivity R and the insertion losses α, i.e. when $R \cdot \exp(-\alpha)$ is sufficiently low, typically less than 0.5. A linear change in the cavity length can be obtained by slowly heating or stretching a section of one of the optical fibers, while measuring the contrast using a fast modulation (0.1 - 1kHz) of the other fiber as shown in Fig. 1. Typically 100 - 200 measurements needs to be performed for establishing a reliable mean value, and each measurement can be carried out fast (typically 50 - 100 measurements/min) by using automated data acquisition. Numerical simulations show that the influence of intracavity reflections will be reduced for higher mirror reflectivity and lower losses.

A large number of measurements have been carried out on a 45mm long 90° bended (7 mm bending radius) silica/silica-oxynitride on silicon single mode waveguide fabricated by plasma enhanced chemical vapor deposition, with core dimensions of $6 \times 9 \mu m$, and with the refractive index matched to single mode silica fibers [10]. The results of a typical measurement on this waveguide is shown in Fig. 3, where the contrast has been measured sequentially for a large number of interference fringes and the insertion loss has been calculated. The total measuring time was 10 min. The average insertion loss based on the averaged contrast has been calculated and is shown in Fig. 3 as solid curve. During the measurements, the output fiber was modulated with a saw-tooth modulation at 0.1 Hz. It is observed on the figure that the intracavity reflections cause a spread of the measured contrast by 0.02 dB (standard deviation) as discussed above, but due to the modulation of the output fiber a varying phase condition is ensured. The average value reaches its final value after less than 150 measurements and remains stable within 0.01 dB. With the current setup, the measured insertion loss for independent measurements on the same waveguide was found to be within 0.1 dB, which mainly was caused by variations in the coupling efficiency. For these measurements, the mirror reflectivities were 15.2% and the insertion loss was measured to 3.39 dB. In a control measurement, the insertion loss of the waveguide was measured to 3.5 dB by measuring the ratio of transmitted light to the light directly from the input fiber, which is in good agreement with the value measured by the Fabry-Perot technique. Since the mirror reflectivity was only 15.2% in this case,
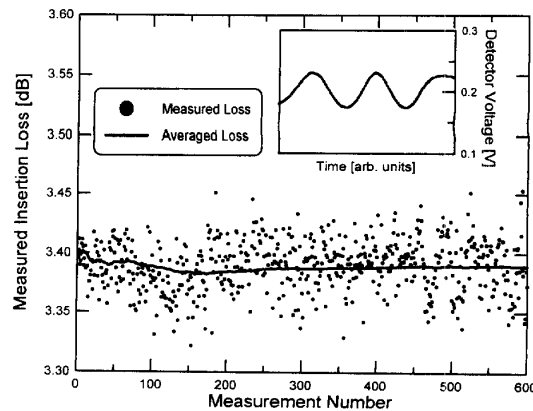

Fig. 3. Typical results from measurements of insertion loss of a planar silica waveguide, with typical interference fringes shown in the insert. Each dot indicates the result from a single Fabry-Perot fringe measurement, and the intracavity reflections cause the spread of the data. The line indicates the average insertion loss based on the average of the measured contrast up to the respective measurement number. The mirror reflectivity was 15.2%.

the technique was applied to demonstrate the measurement technique—although the cut-back method potentially would lead to a higher contrast (see Fig. 2).

III. CONCLUSIONS

A high precision waveguide propagation loss measurement technique, using a Fabry-Perot cavity consisting of the waveguide to be characterized coupled to two polarization-maintaining fibers coated with dielectric mirrors, has been presented. The method is applicable to single mode low-loss silica waveguides, which have been optimized for low coupling losses to silica optical fibers. Presently, the precision of this measurement is limited by the coupling accuracy, but repeatability better than 0.1 dB has been obtained in a not yet fully optimized experimental setup. A double modulation of the cavity decreases the influence of intracavity reflections and improves the accuracy. An optimized experimental setup with automated coupling optimization and data acquisition is expected to improve the precision of this measurement technique.

REFERENCES

[1] Y. Ohmori, "Passive and active silica waveguides on silicon," in *Proc. of ECOC 1993*, paper MoP1.1, 1993.
[2] R. G. Hunsperger, *Integrated Optics: Theory and Technology.* New York: Springer Verlag, 3rd ed., 1991.
[3] H. P. Weber *et al.*, "Loss measurements in thin film optical waveguides," *Appl. Opt.*, vol. 12, no. 4, pp. 755–757, Apr. 1973.
[4] Y. Okamura, S. Yoshinaka, and S. Yamamoto, "Observation of wave propagation in integrated optical circuits," *Appl. Opt.*, vol. 25, no. 19, pp. 3405–3408, 1986.

[5] R. K. Hickernell *et al.*, "Waveguide loss measurement using photothermal deflection," *Appl. Opt.*, vol. 27, no. 13, pp. 2636–2638, 1988.

[6] R. Arsenault, D. Gregoris, S. Woolven, V.M. Ristic, "Waveguide propagation-loss measurement technique," *Opt. Lett.*, vol. 12, no. 12, pp. 1047–1049, 1987.

[7] R. G. Walker, "Simple and accurate loss measurement technique for semiconductor optical waveguide," *Electron. Lett.*, vol. 21, no. 13, pp. 581–583, 1985

[8] R. Regener and W. Sohler, "Loss in low-finesse Ti:LiNbO$_3$ optical waveguide resonators," *Appl. Phys. B.*, vol. 36, pp. 143–147, 1985.

[9] L. S. Yu, Q. Z. Liu, A. Pappert, "Laser spectral linewidth dependence on waveguide loss measurements using Fabry-Perot method," *Appl. Phys. Lett.*, vol. 64, no. 5, pp. 536–538, 1994.

[10] T. Feuchter, C. Poulsen, M. Svalgaard, "Silica waveguide fabrication at mikroelektronik centret," in *Technic. Dig. Laser '94*, Odense, Denmark, p. 17, 1994.