# Cut-Off Wavelength Measurements of Integrated Optical Waveguides

T. Lang, L. Thévenaz, Z. B. Ren, Ph. Robert

One of the most important parameters in the characterization of integrated optical waveguides is the precise determination of the effective cut-off wavelength of the fundamental and the first order mode, since it sets the exact region of single-mode operation. This paper describes an experimental set-up for the measurement of the cut-off wavelengths of integrated optical waveguides, using the technique of spectral light transmission. Measurement results obtained with Ti:LiNbO$_3$ channel waveguides are presented. The effect of different geometrical parameters and fabrication conditions on the cut-off wavelengths of the channel waveguides for both TE and TM mode excitation will be discussed.

## Bestimmung der cut-off-Wellenlängen von integriert-optischen Wellenleitern

Einer der wichtigsten Parameter bei der Charakterisierung integriert-optischer Wellenleiter ist die Bestimmung der effektiven cut-off-Wellenlänge der Grundmode und der Mode erster Ordnung, da diese den exakten Monomode-Operationsbereich definieren. Dieser Artikel beschreibt eine Messanordnung zur Bestimmung der cut-off-Wellenlängen von integriert-optischen Wellenleitern mit Hilfe der spektral übertragenen Leistung. Messergebnisse mit Ti:LiNbO$_3$-Streifenwellenleitern werden vorgestellt. Der Einfluss geometrischer Parameter und Herstellungsbedingungen auf die cut-off-Wellenlängen wird für TE- und TM-Modenanregung untersucht.

## Détermination des longueurs d'onde de coupure des guides d'onde optiques intégrés

Un des paramètres les plus importants dans la caractérisation des guides optiques intégrés est la détermination précise de la longueur d'onde de coupure pour le mode fondamental et le mode de premier ordre, car celles-ci définissent exactement la région monomode. Cet article décrit un banc de mesure mis au point pour la détermination des longueurs d'onde de coupure des guides d'onde optiques intégrés à l'aide de la technique par transmission spectrale. Des résultats obtenus avec des guides à largeurs limitées en Ti:LiNbO$_3$ seront présentés. L'effet des paramètres géométriques et des conditions de fabrication sur les longueurs d'onde de coupure sera discuté pour les modes TE et TM respectivement.

## 1. Introduction

The exact determination of the effective cut-off wavelengths of the fundamental and the first-order mode is one of the most important parameters in the characterization of integrated optical devices. This is of particular interest for waveguide manufacturers to supply the customers with the exact product characteristics.

The theoretical values for the cut-off wavelengths can be obtained by rigorously solving the wave equations, taking into account the refractive index profile and the geometrical structure of the waveguide. However, the calculations for arbitrary waveguides are very complicated and only appropriate for short straight channel waveguides.

For practical use, the experimentally observed effective cut-off wavelengths are of far greater importance. Unfortunately, they strongly depend on the waveguide geometry, the launching conditions and the measurement technique itself [1–4]. Therefore, the effective cut-off wavelength for a certain mode is defined as the wavelength, where this mode is practically absent at the exit of the waveguide [5].

For the measurements of the cut-off wavelengths of optical fibers, two standard reference test methods based on spectral light transmission techniques are recommended by international standard organizations such as the CCITT. These are the single bend and the power step techniques [4–7]. The latter is also well suited to the measurements of cut-off wavelengths of channel waveguides [8–9]. We used an extension of this technique for our cut-off wavelength measurements.

The problems faced in measuring the effective cut-off wavelengths of the short and not pigtailed integrated optical devices are still more delicate to overcome than those for optical fibers. A proper excitation of the waveguides is essential for their correct characterization. On the one hand it has to be assured, that the incoherent light source is exciting all possible modes with the same amount of power. Therefore, the light spot at the entrance of the waveguide should be larger than the strip waveguide width. On the other hand, the light spot should be sufficiently confined to prevent too much light from being injected into the substrate, thus exciting unwanted substrate radiation modes.

Furthermore, at the cut-off wavelength of a mode, the whole energy of the «cutted» mode is transferred into substrate radiation and leaky modes.

All these radiating modes are propagated along the waveguide with a strong attenuation. Due to the small length of the waveguide, they can still play an important role at the exit of the waveguide and provide biased measurements.

## 2. Experimental set-up

Figure 1 shows the experimental set-up. The image of the linearly polarized light from a halogen white light source is projected onto the plane of an aperture (diameter: 100 µm) with a pair of lenses. The aim of the aperture was to select only a small part of the coiled filament to ensure a more uniform and limited illumination of the integrated optical device. By the help of this aperture, the spot size of the launching light beam was sufficiently reduced (to 20 µm) to accomplish an efficient light injection into the waveguide without too much light being lost into the substrate. A high-quality lens such as a microscope objective focuses the image of the source aperture into the waveguide. The numerical aperture of the microscope (NA= 0.35) was chosen to be high enough to excite all the possible guided modes.

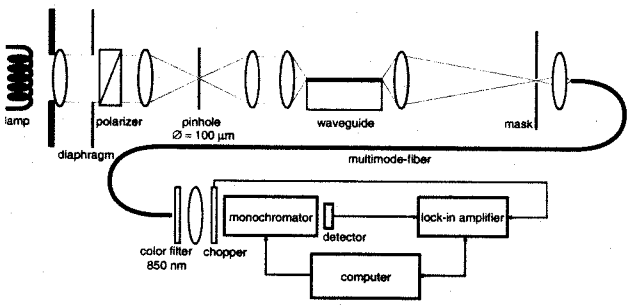

**Figure 1: The experimental set-up for the cut-off wavelength measurements**

The image of the output light of the waveguide is collimated onto the face of a multimode fiber. A prefixed adjustable aperture mask (spatial filter) enables a precise injection of the light coming from the waveguide into the multimode fiber. It also eliminates the leakage light. The fiber output is then directed into a high-resolution spectrometer, after it passes through a chopper and a color filter.

The spectral resolution of the monochromator was chosen to be 8 nm and scanned in the desired wavelength region of 900–1600 nm. The spectrally filtered light at the exit slit of the monochromator is detected by an InGaAs-detector, the signal is then amplified by a lock-in amplifier.

To eliminate the spectral response of the launch and the detection components of the system (such as the broadband lamp, the detector, the monochromator), the spectral output power P(λ) had to be normalized. The best results as a reference power spectrum $P_r(\lambda)$ were achieved by measuring the optical output power spectrum of the whole system without the waveguide. The ratio between the normalized transmission spectrum

$$r(\lambda) = 10 * \log\left(\frac{P(\lambda)}{P_r(\lambda)}\right)$$

is then plotted as a function of wavelength.

## 3. Examined components

We examined following different types of Ti:$LiNbO_3$ channel waveguides for both TE and TM mode excitation: straight waveguides, straight waveguides with polarizers and bent waveguides. The components were X-cut and y- or z-propagation.

Figure 2 gives a typical example of a normalized waveguide output spectrum. The cut-off wavelengths can be determined from these figure. The cut-off wavelength for the fundamental mode ($\lambda_{c00}$) is defined to be the point, at which the transmission spectrum drops by 3 dB after having attained its last maximum (point B). The cut-off wavelength for the first order mode ($\lambda_{c01}$) is defined as the point, where the normalized transmission spectrum starts to rise again (point A, in accordance with [8],[9]).

In another example, the evolution of the normalized transmission spectra as a function of the waveguide width is shown in figure 3, this time for the same waveguide group but for TM mode excitation. The shift of the cut-off wavelengths to higher wavelengths for wider waveguides can clearly be seen.

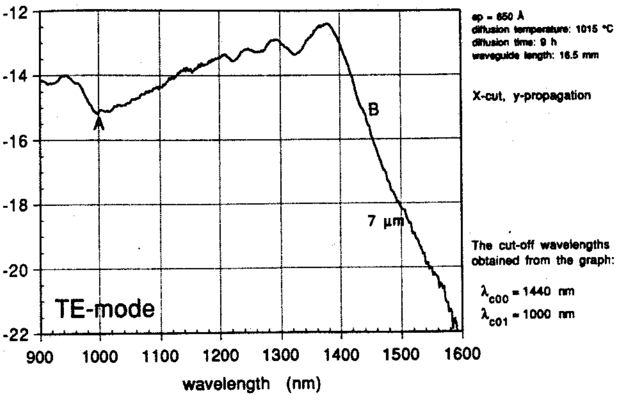

**Figure 2: Typical normalized transmission spectrum of a channel waveguide**

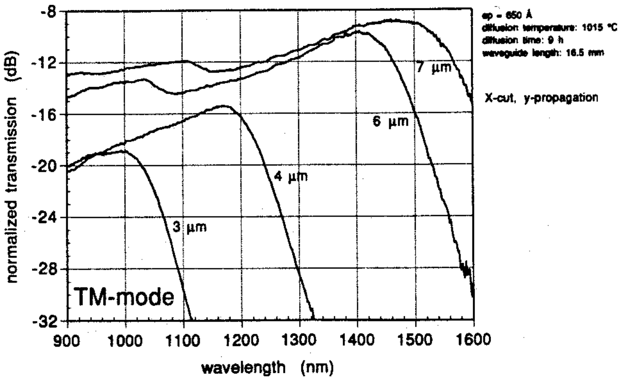

**Figure 3: Normalized transmission spectra for different channel waveguide widths**

In figure 4, the variation of the cut-off wavelengths of the fundamental and first order modes as a function of the Ti-strip width is summarized for another waveguide group. From this figure, the exact single-mode region for each waveguide width can be easily extracted.

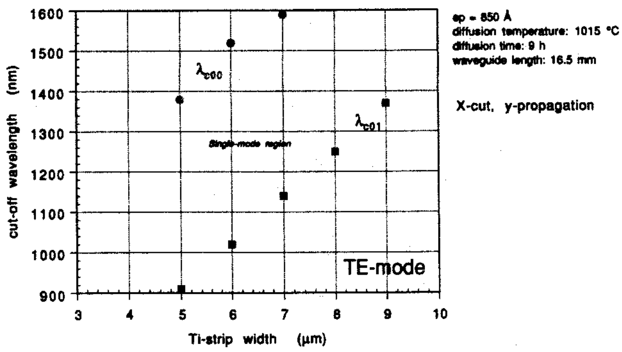

**Figure 4: Variation of the cut-off wavelengths of the fundamental ($\lambda_{c00}$) and first-order modes ($\lambda_{c01}$) as a function of the Ti-strip width**

The transmission spectra of bent waveguides showed, that the induced bends were leading to supplementary radiation losses, that became more important near below the cut-off wavelength of the fundamental mode (and the first order mode) and for smaller curvature radii.

By careful optimization of the waveguide excitation, we could also roughly determine the spectral extinction ratio of the polarizers.

For certain waveguide groups, the influence of the metal-cladding layer, deposited on the waveguides (to make it function as a polarizer), on the cut-off wavelength had been examined. It was noticed that in general the cut-off wavelengths shifted to lower wavelengths (a typical value was p.e. 50 nm).

The strong dependence of the cut-off wavelengths on the strip waveguide width was verified. For wider strip widths, they shifted at a rate of about 50–150 nm/µm to higher wavelengths, depending on the examined components.

The single-mode guiding region of basically all the measured channel waveguides or polarizers was about 400–500 nm large. This could not be achieved with the bent waveguides, where the single-mode region was slightly reduced by decreasing their curvature radii.

## 4. Conclusion

We have presented an experimental set-up for the measurement of cut-off wavelengths for integrated optical waveguides, using the spectral light transmission method. The performance and reliability of the system was verified by the measurements of Ti:$LiNbO_3$ channel waveguides, polarizers and bent waveguides.

To confirm the reproducibility of the system response, we examined certain channel waveguides several times. They always showed a very good agreement of their transmission behaviour, including their cut-off wavelengths.

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### Authors

T. Lang, L. Thévenaz, Z.B. Ren, Ph. Robert
Swiss Federal Institute of Technology of Lausanne (EPFL)
Laboratory of Metrology
CH-1015 Lausanne