Modal Filtering for Nulling Interferometry

First Single-Mode Conductive Waveguides in the Mid-Infrared

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Abstract. This paper presents the work achieved for the manufacturing and characterization of first single-mode waveguides to be used as modal filters for nulling interferometry in the mid-infrared range [4-20 μm]. As very high dynamic range is mandatory for detection of Earth-like planets, modal filtering is one of the most stringent instrumental aspects. The hollow metallic waveguides (HMW) presented here are manufactured using micro-machining techniques. Single-mode behavior has been investigated in laboratory through a technique of polarization analysis while transmission features have been measured using flux relative comparison. The single-mode behavior have been assessed at \( \lambda = 10.6 \, \mu m \) for rectangular waveguides with dimensions \( a = 10 \, \mu m \) and \( b \leq 5.3 \, \mu m \) with an accuracy of \( \sim 2.5\% \). The tests have shown that a single-polarization state can be maintained in the waveguide. A comparison with results on multi-mode HMW is proposed. Excess losses of 2.4 dB (\( \sim 58\% \) transmission) have been measured for a single-mode waveguide. In particular, the importance of coupling conditions into the waveguide is emphasized here. The goal of manufacturing and characterizing the first single-mode HMW for the mid-infrared has been achieved. This opens the road to the use of integrated optics for interferometry in the mentioned spectral range.

Key words. Instrumentation: interferometers – Methods: laboratory – Methods: data analysis – single-mode waveguides

1. Introduction

Since the discovery of a Jupiter-mass companion around 51 Peg by Mayor & Queloz [1995], the next challenges that have been addressed by modern astronomy are the search for habitable telluric planets and the search of indices of life on them. The main challenge being the huge ratio of star to planet flux, Bracewell [1978] and Angel et al. [1986] have suggested to observe in the mid-infrared range. Indeed, in the case of a Sun/Earth system the luminosity ratio is about \( 10^9 \) in the visible while it drops to \( 10^6 \) at 10 μm. The latter authors have shown that reliable biomarkers such as H2O (< 8 μm), O3 (9.6 μm) and CO2 (15 μm) could be researched by spectroscopy in the mid-infrared. At those wavelength, the search for Earth-like planets could use an infrared nulling interferometer in space operating in the [4 - 20 μm] band (Bracewell & McPhie 1979). A nulling interferometer generates destructive interferences for an on-axis star by introducing an achronatic \( \pi \) phase shift between the arms of the interferometer, which results in the complete rejection of the starlight. Aside, for a well-tuned configuration of the baseline, the signal from an off-axis planet will be transmitted since it interferes constructively at the output of the instrument. Thus, this type of instrument provides at the same time high angular resolution through baselines of several tens of meters and high dynamic range through the intrinsic coronographic feature of its transmission map (Léger et al. 1996).

However, reaching a rejection ratio of \( 10^6 \) is subject to three major limitations which are: phase defects that includes residual OPD errors, pointing errors, optics defects and micro-roughness that induce high-frequency defects; Overall and local amplitude shifts; Polarization mismatches due to the rotation of the electric field in the optical train. Concerning the first two points (excepted for residual OPD), authors have shown that leaks could be maintained below \( 10^{-6} \) by implementing spatial filtering using either pinholes (Ollivier & Mariotti 1997) or single-mode waveguides Mennesson et al. (2002). Polarization mismatches could be corrected using polarization maintaining devices.

Filtering with single-mode waveguides is already largely used in near-infrared interferometry. This is done with optical fibers (Coudé du Foresto & Ridgway 1992) or single-mode integrated optics (IO) (Kern et al. 1997). The later option provides, in addition to modal filtering, optical functions like beam combination which is integrated on a small size optical chip. This solution relaxes instrumental constraints like alignment,
mechanical and thermal stability \cite{Malbet1999} and provides to date calibrated astrophysical data from several interferometric facilities \cite{Kervella2003}. The importance of modal filtering is now commonly accepted. In this context of mid-infrared nulling interferometry, the lack of single-mode waveguides has triggered specific studies to develop mid-infrared chalcogenide fibers \cite{Borde2003} and silver-halide fibers \cite{Wallner2004, Wehmeier2004} has also started theoretical studies on conductive waveguides to date calibrated astrophysical data from several interferometric facilities. Wehmeier et al. provides to date calibrated astrophysical data from several interferometric facilities.

The novelty of the technology process brings several unknowns as surface quality, coupling and propagation losses as well as the applied manufacturing process. Then, we present the laboratory workbench built for the characterization phase and the adopted procedure for the specific measurements. In a fourth section are presented the results on the modal behavior and the transmission features of the manufactured HMW. Finally, we discuss the results and the hollow metallic waveguide properties.

2. Modal Filtering with Single-Mode Waveguides

In order to achieve a $10^5$ rejection ratio with a four-telescope configuration, \cite{Leger1995} pointed out the following constraints on the instrument:

- Defects due to optical quality and micro-roughness as well as residual OPD should be kept smaller than $\lambda/2000$ at 10 $\mu$m (i.e. $\lambda/100$ in the visible at 0.5 $\mu$m).
- Pointing errors should remain below 1/80 of the Airy disk in the visible, or 1/1600 at 10 $\mu$m.

To relax those constraints, \cite{Ollivier1997} has first proposed to use pinholes to be placed at the focus of each telescopes. A pinhole with the size of the Airy disk filters out the small-scale defects (i.e. the high spatial frequencies) providing efficient spatial-cleaning. Defects due to dust and polishing are well corrected with a rejection increase of three orders of magnitude. For instance, pinhole filtering permits to reach a rejection rate of $10^6$ when the transmission is degraded by 1% due to dust, while it remains below $10^3$ without filtering. Pinholes efficiency, however, is sensitively reduced for large-scale defects. In particular tilt errors are not significantly corrected with this method and the rejection ratio is improved by less than a factor two. Finally, residual OPD errors cannot be corrected by any type of spatial filtering since they do not affect the intensity distribution of the Airy pattern in the Fourier plane at the telescope focus.

Further improvements are achieved using single-mode waveguides to implement modal filtering. In guided optics theory \cite{Marcuse1974}, a single-mode waveguide does propagate only one mode, the fundamental one, whose amplitude spatial distribution is only constrained by the geometrical and optical parameters of the waveguide, independently of the incoming wavefront. Coupling a corrugated wavefront on the fundamental mode converts the input phase fluctuations into overall intensity fluctuations of the propagating mode. The resulting wavefront at the waveguide output is then cleaned from all phase defects. When placed at the focus of each telescope, the fringe visibility is then only affected by amplitude mismatching which is less drastic than phase defects. However, single-mode waveguides provide neither a correction of the residual OPD nor a correction of overall amplitude unbalancing. Those errors can be corrected with classical fringe tracking and active amplitude matching systems.

\cite{Mennesson2002} provided a quantitative comparison of the optical constraints set respectively by no filtering mode, pinhole filtering and single-mode waveguide filtering to reach a typical rejection ratio of $10^5$. Concerning high-order optics defects and micro-roughness, the wavefront quality at $\lambda=10$ $\mu$m drops from $\lambda/4400$ rms without spatial filtering to $\lambda/400$ rms with pinhole filters and to $\lambda/63$ rms with a single-mode waveguide, that is a gain of almost two order of magnitude. For the telescopes pointing errors, single-mode waveguides become once again very efficient. Reaching a deep null of $10^6$ at 10 $\mu$m requires a control of the tip-tilt up to 1.2 mas rms for 1.5m-class telescopes. In the same conditions, modal filtering with single-mode waveguides relaxes this constraint to 38 mas rms. Local amplitude errors due, for instance, to imperfect coatings reflectivity can also be corrected more efficiently with single-mode waveguides. For the same previous rejection ratio, the relative local amplitude shift to be monitored goes from 0.2% without filtering to 2% with pinhole filtering and to 10% with single-mode filtering.

Concerning polarization mismatching, a way to get rid of this effect is to implement single-mode and single-polarization waveguides in the optical train. This aspect is discussed in Sect. \ref{sect:modal_filtering}

Finally, modal filtering can be implemented after coherent recombination of the beams using only one waveguide rather than placing a waveguide at each telescope focus. The advantage is that any additional phase corruption after filtering is prevented as well as any differential effect due to slightly different waveguides. Modal filtering based on the implementation of single-mode waveguides presents an evident advantage for nulling interferometry where high rejection rates are strongly constrained by the presented factors. Single-mode waveguides are preferred to pinholes since they are efficient for high-order and low-order defects, while the later devices are efficient only for small-scale defects. Therefore, the developing and manufacturing of
single-mode waveguides working in the full band [4 - 20 µm] will provide fundamental improvements for nulling interferometry missions like Darwin and TPF.

### 3. Geometry and Manufacturing of the Waveguides

A proposed solution to develop mid-infrared modal filters are hollow metallic waveguides (HMW), which benefit of a strong heritage from microwave engineering and which are widely used in the radioastronomy field. Light propagation with HMW is based on multiple metallic reflections of the radiation inside the cavity. HMW have been selected as a candidate because they are able to cover the full Darwin band [4 - 20 µm] although this is done through the implementation of three or four single-mode sub-bands. The question of the full coverage of the band is similarly addressed when using dielectric solutions since this reduces the number of infrared glassy materials that can be exploited.

Within the frame of our study, the adopted geometry for our devices is a rectangular shape (see Fig. 4) with sides \( a \) and \( b \) (and \( a \geq b \)). Based on our study on well established microwave models [Rizzi 1988], we have computed the electric field distributions of the different propagated mode as well as their respective cut-off wavelength (i.e. the wavelength above which the mode is not propagated anymore). Thus, for a waveguide geometry fulfilling the condition \( a=2b \), the fundamental mode is the linearly polarized TE\(_{10}\) with a cut-off wavelength \( \lambda_{c(TE_{10})} = 2a \). The first higher-order mode is the mode TE\(_{01}\) with a cut-off wavelength \( \lambda_{c(TE_{01})} = a \) and with a linear polarization orthogonal to the TE\(_{10}\) fundamental mode. Consequently, a waveguide with the specified geometry has a single-mode range defined by those two cut-off wavelengths, that is \( a < \lambda < 2a \). Note that the single-mode range remains unchanged with a geometry verifying \( b \leq \frac{a}{4} \) while it becomes \( 2b < \lambda < 2a \) when \( b \geq \frac{a}{4} \). It is then possible to tune the single-mode range of the rectangular waveguide by changing its geometry. Under those conditions, we have fixed for HMW an etching depth of \( a = 10 \) µm while their width ranges from \( b \approx 4.5 \) µm to \( b \approx 10 \) µm (see Table 1).

Considering what previously said, this geometry theoretically ensures a single-mode behavior at \( \lambda = 10.6 \) µm for those waveguides that comply with the condition \( b \leq 5.3 \) µm. The waveguides fulfilling the opposite condition \( b \geq 5.3 \) µm will have a multi-mode behavior at 10.6 µm. Our work, based on characterization experiments at 10.6 µm, aims then to enhance experimentally the difference in behavior between single-mode type and multi-mode type waveguides.

The manufacturing of a hollow metallic waveguide is based on a standard micro-technology etching process of silicon substrate plus anodic bonding of a Pyrex cover on the silicon structure. The process is described in Fig. 1. The result is a chip containing rectangular waveguides spaced by 300 µm with sub-micron accuracy, with inside walls coated with gold. The total length of a waveguide is 1 mm. To avoid a direct transmission through the silicon substrate, the external facets of the chip are also coated with gold by evaporation process.

The results reported in this paper are related to channel waveguides both with and without tapers. A taper is a smooth transition between a multi-mode channel waveguide and a single-mode one, similar to impedance cornets in millimeter astronomy. This structure added at the input and output of the waveguide relaxes the coupling constraints. The dimensions of the taper are 40 µm width by 10 µm depth (see Fig. 4). The 1-mm length waveguides includes the tapers when they are added. The right panel of Fig. 1 presents a Scanning Electron Microscope (SEM) image of a 5 µm × 10 µm component. Table 1 summarizes the geometrical parameters of the tested components and provides the reference names used through the paper. All the waveguides are described with the reference Gxx where xx is a specific number. The letter “T” is added if the waveguide supports a taper.

### 4. Laboratory Validation

The laboratory workbench aims at testing and analyzing the single-mode behavior and the propagation features of the manufactured waveguides. The optical layout of the injection workbench is provided in Fig. 2. The chip containing the channel waveguides is supported on a three-axis positionner...
with fine step resolution (~1 µm) to co-align the component with the optical axis. Considering the dimensions of the waveguide aperture, a major constraint is put on the optical quality of the input beam. Therefore, we use an aspherical fast optics with numerical aperture f/1.15 to focalize the beam on the waveguide aperture, providing a spot with 30 µm full-width. A beam-expander permits to fill the 22-mm clear aperture of the focalization lens. The output flux is collected with a f/1.5 lens that images the waveguide output on the camera focal plane. The detection stage supports an uncooled 320×240 micro-bolometer array detector sensitive from 8 µm to 12 µm. A grid polarizer is placed either before the component (i.e., into the collimated beam) or after the component to select the desired polarization to be analyzed. The extinction ratio of the polarizer at λ=10.6 µm is 185:1, which is equivalent to a polarization degree of 99.4%. The Gaussian beam distribution of the laser is highly flattened since the collimator C with f=254 mm is overfilled. Thus, the spot at the waveguide input can be considered as diffraction-limited.

The linear polarization of the CO₂ laser has been converted into elliptical polarization by adding a quarter-wave plate in the ray path. This permits to force any polarization direction at the waveguide input. The elliptical polarization of the source is characterized by the curve in the left panel of Fig. 5 that plots the calibrated flux level of the source as a function of the angular position of the polarizer.

The 300 µm spacing between the different channel waveguides is used as a qualitative validation criterion for the observation of the waveguide output. Indeed, we can observe successive bright spots when translating the chip by the separation of 300 µm, which confirms that the detected flux has been guided along the waveguide. For quantitative relative flux measurements, a flat field correction is applied and the mean level of thermal background is subtracted as presented hereafter.

For each image with a flux I_{raw} per pixel, a dark image I_{dark} corresponding to the response of the array to a spatially uniform source is recorded. The flat field correction is applied for each single pixel by computing a corrected image I_{flat} given by

\[
I_{\text{flat}} = \frac{I_{\text{raw}}}{I_{\text{dark}}} \]  
\[ (1) \]

where \(I_{\text{dark}}\) is the pixel average value of the dark image. The mean level of the thermal background is obtained by computing the pixel average \(\bar{I}_{\text{BG}}\) of a sub-frame of \(I_{\text{flat}}\) where the background is uniform and where no signal is detected. The final corrected image \(I_{\text{cor}}\) is given by

\[
I_{\text{cor}} = I_{\text{flat}} - \bar{I}_{\text{BG}} \]  
\[ (2) \]

As an example, Fig. 4 presents a cross-sectional view of the correction stage as well as a calibrated image of a waveguide output. The artifacts visible on the left panel of Fig. 3 are filtered out with the applied correction.

Finally, to perform transmission measurements of a waveguide, we compare the calibrated flux without the waveguide \(I_{\text{out}}\) and the calibrated flux through the waveguide \(I_{\text{in}}\). The estimated relative transmission of the waveguide is thus

\[
T_{\text{ext}} = \frac{I_{\text{in}}}{I_{\text{out}}} \]  
\[ (3) \]

where \(I_{\text{in}}\) is the transmitted power through the waveguide and \(I_{\text{out}}\) is the transmitted power without the waveguide. \(T\) is defined as the total throughput of the component.
of the grid polarizer. This result is obtained with the sample G36-T (see Table 1) designed to be single-mode at $\lambda=10.6 \mu m$. The angular positions $0^\circ$ and $180^\circ$ correspond to the polarizer oriented along the $y$-axis in Fig. 4, which theoretically matches with the total extinction of the electric field oriented orthogonally. The plot shows that the electric field can be experimentally totally extinguished at these two extreme angular positions. The first higher order mode being the $TE_{01}$ according to the geometry of G36-T, this result shows that no electrical field oriented along the $y$-axis can be excited at a wavelength of $10.6 \mu m$, which confirms the single-mode behavior of the waveguide.

Polarization tests have been also made for waveguides designed to be multi-mode at $\lambda=10.6 \mu m$. The results on the tested sample G42-T (see Table 1) have been reported here. The propagation modes theoretically existing in the cavity are the fundamental mode $TE_{10}$ with its electric field oriented along the $x$-axis, the mode $TE_{01}$ with the electric field oriented along the $y$-axis, and the modes $TE_{11}$ and $TM_{11}$ with a distribution of the electric field both in $x$ and $y$ directions (Jordan & Balmain, 1985). Since $TE_{11}$ and $TM_{11}$ are odd modes, it is assumed that no energy will be coupled on those modes if the excitation field is centered on the waveguide aperture. The right panel of Fig. 5 shows the flux measured after the sample G42-T as a function of the angular position of the polarizer.

The curve presents a strong decrease around $100^\circ$, but for any position of the polarizer between $0^\circ$ and $180^\circ$ the result shows that it is always possible to detect flux transmitted through the waveguide. The minimum value is about 150, which is above the noise limit. Thus, no single-polarization state can be measured with G42-T, which shows that higher order modes can propagate into the waveguide.

For the single-mode G36-T component, the error bars measured for the total extinction are limited by the thermal background fluctuations ($\sim 16$ A.U. in Fig. 5). The maximum flux level is about 600 A.U., which guarantees an accuracy of $\sim 2.5\%$ on the measurement. It is also interesting to note that the maximum flux detected with the multi-mode waveguide G42-T ($\sim 2100$ A.U.) is three to four times the maximum flux detected with the single-mode waveguide G36-T ($\sim 600$ A.U.). This can be explained by power coupling on higher order modes that can propagate into the multi-mode waveguide.

In Table 1 are reported the results of the modal characterization of a precise set of waveguides at $\lambda=10.6 \mu m$. The modal behavior of the samples is given based on the results of polarization tests. Our results show that a cut-off is experimentally observed for waveguide widths above $w=5.1 \mu m$. This confirms the single-mode range predicted theoretically in Sect. 5.

The analysis based on polarization tests offers a quantitative measurement of the modal behavior that is based on flux level measurements. This method can be compared to the near-field imaging method used in Laurent (2003) to characterize fibers for the near-infrared, which is based on a qualitative analysis of the output intensity distribution. With
this last method, the discrimination between the fundamental and the first mode turns to be more difficult when analyzing the field spatial distribution rather than implementing a flux measurement.

5.2. Waveguide Transmission

In a simple approach, the total throughput $T$ of a channel hollow metallic waveguide can be separated into 1) input coupling efficiency $C_{in,i}$ on the mode $i$ 2) propagation losses $P_i$ of the mode $i$ 3) output coupling efficiency $C_{out,i}$ on the mode $i$ 4) quality factor $\eta_i$ through the expression

$$T = \sum_{i=1}^{n} C_{in,i} \cdot P_i \cdot C_{out,i} \cdot \eta_i$$  \hspace{1cm} (5)

which simply becomes in the single-mode case

$$T(\%) = C_{in} \cdot P \cdot C_{out} \cdot \eta$$  \hspace{1cm} (6)

The term $P$ is dependent on the waveguide length. The quality factor $\eta$ includes a term of impedance mismatch comparable to Fresnel losses for near-infrared fibers and the losses due to technological imperfections at the taper input and output that degrade the coupling efficiency and that are not considered when computing the overlap integral. $\eta$ is dependent on the fabrication process and can vary from one waveguide to another. The term $P \cdot \eta$ is defined as the excess losses and corresponds to the physical quantity that can be measured experimentally. It is therefore a worst-case value of the propagation losses $P$ of the waveguide.

The input and output coupling efficiencies must then be evaluated to estimate the propagation term $P \cdot \eta$. They have been estimated numerically by computing the two-dimension overlap integral between the excitation field and the dominant mode profiles at the waveguide input and output. The excitation field at the waveguide input is a plane wave focused by a lens with focal length $f$ and a clear aperture $D$. The shape of the field can be modeled with an Airy function given by

$$E_{exc}(x,y) = \frac{f}{D} \frac{J_1(D)}{J_0(D)} \frac{\pi \sqrt{(x-d)^2+(y-e)^2}}{\lambda \sqrt{(x-d)^2+(y-e)^2}} \hspace{1cm} (7)$$

where $E_{exc}$ stands for the electric excitation field amplitude, $f$ is the focal length of optics $I_1$ (see Fig. 2) and $D$ its clear aperture. $J_1$ is the first order Bessel function, $d$ and $e$ are the lateral displacement with respect to the center of the waveguide aperture respectively in the $x$ and $y$ directions. Since the $E_{exc}$ has a radial symmetry and the waveguide aperture two symmetry axis, it can be shown that the maximum coupling efficiency occurs when the excitation field is centered in the waveguide input (i.e $d=e=0$). Losses $\leq 1\%$ occur for a displacement $d$ or $e$ of 1 $\mu$m (Schäfer 2003). Thus, in the next sections the coupling efficiencies are considered to be computed for a centered excitation field.

Due to the quality factor $\eta$, the experimental coupling efficiency might differ from the theoretical values. It is possible to evaluate the order of variation between experience and theory by changing the diameter (i.e. the numerical aperture) of the injection spot given in Eq. (4) and measuring the variations of the transmitted flux.

The plot of Fig. 6 compares the normalized coupling efficiency on an aperture with a taper obtained with the model approach and with the experimental data. The coupling efficiency curve has been normalized to one because it is only possible to make a relative comparison of the different data via differential flux measurements. It is not possible to extract the absolute values of the efficiencies with our current test configuration. Doing this test with a tapered waveguide has the advantage of observing experimentally a maximum for the coupling efficiency curve, which would have not be possible testing a waveguide without taper for which a maximum occurs below $f/0.5$. The cross-curve first shows that a maximum coupling efficiency is obtained experimentally for $f/D=1.6$, which matches with the value computed with the model. This results tells that the method of the overlap integral can be applied in our case. Aside from the maximum coupling, the experimental curve presents a significant degradation - up to 20% - with the theory. That puts on evidence the importance of the quality factor $\eta$ in degradation of the coupling efficiencies.

We report in Table 1 the results of the characterization phase of HMW at $\lambda=10.6\mu$m. In Eq. (6) $T$ is measured experimentally. $C_{in}$ and $C_{out}$ are obtained numerically which permits to extract the excess losses $\eta$. The excess losses is the only transmission feature that can be extracted from experimental measurements and is therefore given in dB while the propagation losses are given in dB $\cdot$ mm$^{-1}$.

The output coupling efficiency has been computed with the following parameters: the imaging optical system has a focal length $f=38.1$mm and a clear diameter $D=16.5$mm, which gives a numerical aperture $f/2.99$. At $\lambda=10.6\mu$m, the imaging optics is limited to 28$\mu$m resolution and a typical aperture of 10$\mu$m×10$\mu$m will not be resolved. This results in the diffraction-limited energy distribution shown in Fig. 5.
It is not the optimal one when considering 40\mu m for any of the polarization direction. For the three graphs, the flux level is reported in Arbitrary Units (A.U.). Experimentally, the excess losses of each mode with our setup. For multi-mode waveguides, it is not possible to separate it is done in Table 1. When considering tapered waveguides, a clear transition can be observed in terms of transmission as predicted by the theory. Filtering the higher order modes results in significant drop in flux, which corresponds to the transition between single-mode and multi-mode regime. The same aspect is encountered with traditional dielectric infrared fibers.

As a consequence, a Bessel distribution is assumed with the numerical aperture of f/2.29 to compute the output coupling efficiency \( C_{\text{out}} \).

The injection tests have been carried out with the workbench configuration presented in Sect. 4 in which the injection lens \( L_1 \) has a numerical aperture of f/1.15. Although this aperture is not the optimal one when considering 40\mu m x 10\mu m tapers, it is the best option for waveguides without tapers.

For multi-mode waveguides, it is not possible to separate experimentally the excess losses of each mode with our setup. However it is still possible to compare the total throughput as it is done in Table 1. When considering tapered waveguides, a clear transition can be observed in terms of transmission as predicted by the theory. Filtering the higher order modes results in significant drop in flux, which corresponds to the transition between single-mode and multi-mode regime. The same aspect is encountered with traditional dielectric infrared fibers.

Theoretically, propagation losses for rectangular single-mode waveguides with \( a=10\mu m \) are \( \sim 0.8 \) dB.mm\(^{-1}\) at 10.6\mu m (see Schanen 2003 and appendix A). A static conductivity of \( \sigma_0=4.1\times10^7 \) S.m\(^{-1}\) has been assumed for gold coating. Experimentally, excess losses of 2.5 dB to 4 dB over 1-mm are measured in this study. Firstly, this difference results from a poor quality factor at the waveguide input and output that strongly affects the coupling efficiency. The important dispersion in losses for the sample G46 in Table 1 could be explained with a similar dispersion in the technological repeatability, which could be improved in a next technological run. However, the clear distinction in transmission between single-mode and multi-mode waveguides show that the quality factor does not prevent from assessing the modal properties of those waveguides. New considerations on waveguide losses are presented in Sect. 5.

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**Fig. 5.** a: Characterization curve of the elliptically polarized source. - b: Polarization measurements for the single-mode waveguide G36-T at \( \lambda=10.6 \) \mu m with \( a=10 \) \mu m and \( b=5.1 \) \mu m. The output flux can be totally extinguished at angular positions 0° and 180° with \( \sim 2.5\% \) accuracy - c: Polarization measurements for the multi-mode waveguide G42-T at \( \lambda=10.6 \) \mu m with \( a=10 \) \mu m and \( b=9.2 \) \mu m. A strong variation of the flux level is observed but it is not possible to achieve a total extinction of the output flux for any of the polarization direction. For the three graphs, the flux level is reported in Arbitrary Units (A.U.).

**Table 1.** Description of tested waveguides and experimental performances over 1 mm length. The sign “<” in the table means the computation is not applicable. The waveguides supporting a taper are referred as Gxx-T. The modal behavior has been assessed through polarization tests. For \( b \leq 5.1 \mu m \), the transmitted flux can be totally extinguished at 0° angular position of the polarizer. Above this width, flux variations are still observed but it is not possible to extinguish the flux anymore. In the single-mode case (SM), the coupling efficiency on the fundamental mode has been computed with the overlap integral method for the different geometrical apertures. In the case of waveguides with tapers (G46-T and G36-T), the coupling efficiencies have been computed for the taper aperture 40\mu m x 10\mu m, which results in similar values of \( C_{\text{in}} \) and \( C_{\text{out}} \). The excess losses include the propagation losses of the waveguide and the effects of the quality factor \( \eta \). Using a taper improves significantly the coupling both in single-mode and multi-mode case (MM). Multi-mode waveguides with taper transmit about 4.5% of the total flux while single-mode waveguides with tapers transmit about 2% of the total flux.
6. Discussion

This section discusses the results obtained in this work and proposes improvement perspectives. The following properties of HMW are also detailed: operational spectral range, wavelength-dependent losses and polarization properties.

The analysis through polarization tests allowed showing the single-mode behavior of waveguides at 10.6 μm and estimating it with ~2.5% accuracy due to background fluctuations. This first reported measurement confirms that conductive waveguides are suitable for manufacturing single-mode waveguides in the mid-infrared.

The optical quality of the waveguide input and output facets (included within the factor η in the paper) greatly affects the excess losses. At the moment, the chips containing the waveguides are cut out from the wafer using dicing and cleaving processes, which results in unexpected irregularities around the waveguide inputs. Different technological options have already been considered, which should reduce the dispersion on quality and then improve the technological repeatability.

The experimental results have shown the fundamental importance of coupling optimization at the waveguide input and output. In this first technological run, a strong priority has been set on manufacturing rather than on design, so the computed coupling efficiencies in Tab. 1 are not optimized. Thus, we are confident that coupling efficiencies can be improved through a more stringent design of the tapers in the next run.

One of the most recurring issue for spatial or modal filtering is the effects of chromatism. With optical and infrared waveguides, modal filtering can be implemented in a spectral range where the device is single-mode. We have seen that for conductive rectangular waveguides with dimensions a and b=a/2, the single-mode domain is given for a ≤ λ ≤ 2a, which represents a 66% bandwidth centered on λ = 1.5a μm. Thus, this property is used to divide the [4 - 20 μm] band into a relatively low number (three or four) of single-mode sub-bands.

However, it is not recommended to apply this reasoning straightforward since the propagation losses within the same sub-band are highly chromatic. Schanen (2003) has derived the well-established losses calculations in millimeter regime to the mid-infrared domain using a Drude’s modal approach for the metallic coating. Appendix A presents the main steps of the calculation for this approach. The author has expressed the attenuation coefficient of the dominant mode TE_{10} as a function of λ, λ_c, and (n,k) the real and imaginary indices of gold in the mid-infrared. The conclusion contains the following two points: first, the average losses in a given single-mode sub-band are higher at shorter wavelength than at longer ones; secondly, within the same sub-band, losses are minimized for wavelengths close to the lower cut-off (i.e. λ_c = a) and increase continuously when λ approaches the higher cut-off (i.e. λ_c = 2a) \(^1\). Dividing the range [4 - 20 μm] is therefore a trade-off between the bandwidth and the average losses of a single-mode sub-band.

Following this analysis, a trade-off is proposed dividing the [4 - 20 μm] band into four single-mode sub-bands B_1=[4 – 6 μm], B_2=[6 – 10 μm], B_3=[10 – 16 μm] and B_4=[16 – 20 μm] using as modal filters HMW with a verifying a=4 μm for B_1, a=6 μm for B_2, a=10 μm for B_3 and a=16 μm for B_4. The computed average losses for each sub-bands are respectively 3.5 dB.mm\(^{-1}\) for B_1, 2.7 dB.mm\(^{-1}\) for B_2, 1.5 dB.mm\(^{-1}\) for B_3 and 0.6 dB.mm\(^{-1}\) for B_4.

Compared to the computed performances, the transmission values presented in Table 1 are also affected by the surface roughness of the metallic walls, which is not taken into account yet in the loss model. To date a gold coating with rugosity lower than 50nm rms can be deposited but the roughness has increased during the anodic bonding process. A better control of this last step is achievable, making roughness lower.

Schanen (2003) has shown that an efficient filtering of 10^{-7} (~ 70 dB) is already reached after a 10μm length (~ 100 μm) of the waveguide (see appendix B). This implies that integrated optics functions (e.g. IO beam combiner) could be implemented over short propagation distances, typically lower than 1-mm length, reducing then the propagation losses. Fabricating shorter functions is a point that has already been addressed and is technically achievable.

Finally, HMW present interesting polarization properties with respect to the issue of polarization control presented in Sect. 1. A single-mode rectangular metallic waveguide presents a single-polarization behavior, which means the implemented device is able to force a linear polarization at its input. Under those conditions, the beams combined in the waveguide do not present polarization mismatching anymore. Since the differential rotation of polarization planes has to be controlled down to 0.002 rad to achieve a 10^6 rejection ratio (Mennesson et al. 2002), single-polarization waveguides present an advantage to get rid of this constraint although this could occur at the expense of power transmission.

7. Conclusions

This study has focused on the feasibility of manufacturing rectangular Hollow Metallic Waveguides to be used as modal filters thanks to their single-mode behavior. This offers an original instrumental solution in a spectral range where similar possibilities are only recently emerging. The demonstrated single-mode behavior is considered as the major result of this study. A quantitative measurement based on experimental polarization analysis has shown the single-mode behavior of the manufactured waveguides with ~2.5% accuracy and has been compared with results obtained on multi-mode waveguides. Single-mode HMW show that a single-polarization state can be maintained into the waveguide, which is a certain advantage for polarization control in nulling interferometry. The result of this

\(^1\) The attenuation coefficient of a propagating mode tends theoretically to infinity when λ equals the cut-off wavelength.

\(^2\) The fourth waveguide is single-mode up to λ = 32 μm, but the definition of the Darwin band limits it to λ = 20 μm.
study also states that improving the total throughput of such waveguides is mainly a matter of increasing the coupling efficiencies at waveguide inputs and outputs. This can be increased significantly through the designing of well-adapted horns.

In a medium-term scale, single-mode channel waveguides could be extended to the manufacturing of planar integrated components. Those devices could ensure simple interferometric functions (recombination, photometric control), which compactness and stability would be very attractive for future interferometry space missions.

Appendix A: Deriving of the theoretical propagation losses of the TE$_{10}$ mode

This annex presents the main results contained in Schanen (2003). In the microwave regime – i.e. for frequencies ranging from 1 to 1000 GHz – the computation of the theoretical propagation losses is based on the modelization of the skin “skin effect” (Rizzoli 1988). It is well-known that the tangential electric field at the surface of a perfect metallic medium equals zero. For a real metallic coating, the finite conductivity induces the presence of a small tangential component of the electric field in the metal. As a consequence, some power flows through the lateral walls of the waveguide.

To extract the attenuation factor of the guided mode, we identify the average guided power lost in between the coordinates $z=0$ and $z=L$ of the propagation axis with the power flowing through the metallic walls on an equivalent length. In this approach, the static conductivity of the metal $\sigma_0$ has to be considered as long as we remain in the microwave regime since the frequency of the electromagnetic wave is much lower than the collision frequency of the electrons ($\sim 10^{13}$ Hz (Quéré 1988)). In the mid-infrared domain, the radiation frequency is much higher ($\sim 3 \times 10^{13}$ Hz) and the conductivity of the metal $\sigma$ becomes frequency-dependent following the Drude model (Quéré 1988). This has been taken into account in the proposed approach.

The power dissipated in the walls $W_J$ between $z=0$ and $z=L$ is obtained by computing the flux of the Poynting vector across the waveguide section at the corresponding $z$-coordinate. This results in

$$W_J = (1 - \exp(-2\alpha_L L)) \int_{\text{section}} (E \times H^*).z dxdy \quad (A.1)$$

where $E$ and $H$ are respectively the electric and magnetic field, $\alpha_L$ the attenuation factor. Using the equations of $E$ and $H$ fields for the TE$_{10}$ fundamental mode (Jordan & Balmain 1985), Eq. (A.1) becomes

$$W_J = (1 - \exp(-2\alpha_L L)) C \frac{2}{\lambda^2} ba^3 \sqrt{\frac{\mu_0}{\varepsilon_0}} \left| 1 - \frac{1}{\lambda_c^2} \right| \quad (A.2)$$

where $C$ is a field constant, $\lambda$ the operating wavelength, $\lambda_c$ the TE$_{10}$ cut-off wavelength, $a$ and $b$ the waveguide dimensions.

To compute the tangential component of the $E$ field in the metal, we employ the Maxwell equation

$$\frac{d}{dz} H_x - \frac{d}{dx} H_z = -j\omega \varepsilon E_y + \sigma E_y \quad (A.3)$$

where $\varepsilon$ and $\sigma$ are the complex permittivity and conductivity of the metal obtained through the Drude model of a metal, $\omega$ the radiation frequency. At infrared wavelengths, the commonly used approximation $\text{Re}[\sigma] >> \text{Re}[\omega]$ is not valid anymore and both terms must be maintained in Eq. (A.3). The wave vector $k$ of TE$_{10}$ mode presents a component $k_z$ along the propagation axis, as expected in the case of a perfect metal, and a component along the $y$-axis (see Fig. 4) corresponding to a slight penetration of the $E$ field in the metal. Quantities $k_z$ and $k_x$ are determined using the formalism of the reflection of an electromagnetic radiation at a metallic surface. We derive

$$k_z = j \frac{\omega}{c} \sqrt{1 - \left( \frac{\lambda}{\lambda_c} \right)^2} \quad (A.4)$$

$$k_x = j \frac{\omega}{c} \sqrt{(n - jk)^2 - (1 - \left( \frac{\lambda}{\lambda_c} \right)^2)} \quad (A.5)$$

where $N = n - jk$ is the complex refractive index of the metal. Quantities $n$ and $k$ are accessible at $\lambda = 10 \mu m$ through measurement tables in Ordal et al. (1983). Solving Eq. (A.3) we obtain an expression of the $E$ field in the metal following

$$E_x = C \frac{1}{j\omega \varepsilon - \sigma} \frac{k_y^2 + k_z^2}{k_y} \exp(-j\omega t) \exp(k_y y + k_z z) \quad (A.6)$$

The expressions of the conductivity $\sigma$ and permittivity $\varepsilon$ follow

$$\sigma = \frac{\sigma_0}{(1 - j\omega \tau)^2} \quad (A.7)$$

$$\sigma_0 = \varepsilon_0 \varepsilon_\infty \tau (\omega_p)^2 \quad (A.8)$$

where $\omega_p$ is called “plasma frequency” and characterizes the medium (Ordal et al. 1983). The power flowing through the metallic walls is obtained in an analog way of Eq. (A.1) through

$$P_J = \frac{1}{2} \text{Re}[\sigma] \int_V E_x E^*_x dV \quad (A.9)$$

where $\text{Re} [ ]$ is the “real part” operator. The quantity $dV$ is the elementary volume that takes into account the walls surface and the penetration depth of the $E$ field in the metal. We derive the following expression for $P_J$

$$P_J = \frac{1}{2} \frac{C^2}{\sigma^2 + (\omega_p)^2} \left| \frac{(k_y)^2 + (k_z)^2}{k_x} \right| \times b \frac{1}{2 \text{Re}[k_x]} \left| 1 - \exp(-2\alpha_L L) \right| \quad (A.10)$$

From Eq. (A.7) and (A.8), the term $(\text{Re}[\sigma]/(j\omega \varepsilon - \sigma^2))$ can be simplified into $1/\sigma_0$, where $\sigma_0$ is the static conductivity of the metal. Using the fact that
\[ k^2 - n^2 > 1 > 1 - \left( \frac{\lambda}{\lambda_c} \right)^2 \]  

we derive the following expressions

\[ \text{Re}[k] = \frac{\omega_c}{c} \left( 1 + \frac{1 - \left( \frac{\lambda}{\lambda_c} \right)^2}{2(n^2 + k^2)} \right) \]  

(A.12)

and

\[ \left| \left( k_x \right)^2 + \left( k_y \right)^2 \right| = \frac{\omega_c}{c} \left( n^2 + k^2 + 2 \left( 1 - \left( \frac{\lambda}{\lambda_c} \right)^2 \right) \frac{n^2 - k^2}{2(n^2 + k^2)} \right) \]  

(A.13)

Eq. A.12 and A.13 are used to derive the complete analytical expression of Eq. A.10. The attenuation factor \( \alpha_g \) is now obtained by assuming that \( W_f = 2P_f \). The attenuation factor, given in Np.m\(^{-1} \) (Nepers per meter) verifies

\[ \alpha_g = \frac{\pi}{2} \frac{1}{\sigma_0} \sqrt{\frac{\epsilon_0}{\mu_0}} \left( \frac{n^2 + k^2 + 2 \left( 1 - \left( \frac{\lambda}{\lambda_c} \right)^2 \right) \frac{n^2 - k^2}{2(n^2 + k^2)}}{k \left( 1 + \frac{1 - \left( \frac{\lambda}{\lambda_c} \right)^2}{2(n^2 + k^2)} \right)} \right) \]  

(A.14)

Eq. A.14 is converted into more useful units dB.m\(^{-1} \) by multiplying the expression by factor 8.68 (Jordan & Balmain 1985).

### Appendix B: Deriving of filtering length for higher order modes suppression

We consider a rectangular HMW with \( a=2b \). The single mode domain ranges from \( \lambda=a \) to \( \lambda=2a \). The cut-off wavelength of the first higher order mode \( TE_{01} \) is \( \lambda_c=a=2b \).

In the single-mode regime, the propagation constant \( \gamma \) of the \( TE_{01} \) mode as it appears in exp(\( -\gamma z \)) is real and equals

\[ \gamma = \frac{2\pi}{\lambda} \sqrt{\frac{\lambda^2}{\lambda_c^2} - 1} \]  

(B.1)

with \( \lambda > \lambda_c \). The term \( \gamma \) is transformed into attenuation factor \( \alpha \) of the mode in dB.m\(^{-1} \) through (Jordan & Balmain 1985)

\[ \alpha = 8.68 \times \gamma \]  

(B.2)

Assuming a HMW with dimensions \( a=2b=10\mu m \), the attenuation \( \alpha \) factor is lower as \( \lambda \) is closer to \( \lambda_c \). Let us consider a worst case with \( \lambda=10.1 \mu m \). At this wavelength, Eq. B.1 provides an attenuation factor that equals \( \alpha=0.76 \text{ dB.m}^{-1} \). Thus the waveguide length required to attenuate the higher order mode by 70 dB (\( 10^{-7} \)) is 92 \( \mu m \). As the wavelength increases, the attenuation factor increases as well and the required filtering length becomes shorter.

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