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Single mode mid-infrared silver halide asymmetric flat waveguide obtained from crystal extrusion

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Abstract: A flat waveguide for the middle infrared was made by co-extrusion of two silver halide crystals of different chemical compositions. The transmission of the waveguide and its modal behavior was studied using a Fourier Transform Spectrometer and a dedicated optical bench. Analyzing this spectrum, we were able to obtain the cut-off wavelength of the waveguide. We observed a single mode behavior for wavelengths longer than 8.83 μ m, in good agreement with the theoretically expected values. This novel procedure is ideal for tailoring the properties of the waveguide for specific applications, in particular the spectral range where it exhibits a single-mode behavior. It can thus be applied to achieve modal filtering for mid-IR astronomical interferometers (e.g. beam combiners, nullers, etc.).

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OCIS codes: 230.7390 (planar waveguides); 130.3060 (infrared); 160.3130 (integrated optics materials).

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1. Introduction

Optical waveguides for the middle infrared (MIR) 6-20 μm spectral range have not been widely reported, in spite of their potential use as modulators [1], detectors or sensors [2,3], or as other basic elements in integrated optics devices for applications such as nulling stellar interferometry [4]. The lack of low-loss materials for realization of MIR waveguides in this spectral range has limited the research in this field. Silver halide crystals, e.g. $\text{AgCl}_x\text{Br}_{1-x}$, are promising candidates for the realization of MIR waveguides due to their high transparency in the 3–30 μm spectral range. Indeed, silver halides have been used in the past for fabrication of MIR fibers, for a variety of applications, including single mode fibers [5], fiber-flattened waveguides [6], and multi-mode diffused planar waveguides [7,8]. In this work we report on the first single mode step-index asymmetric planar waveguides made of silver halides, and devoted to mid-IR applications. The interest in such step-index waveguides relies on their better confinement and the possibility to easily modify the fabrication parameters (waveguide-substrate birefringence, thickness) in order to obtain the desired transmission or modal behavior. The context of this work is the search for efficient modal filter waveguides devoted to nulling interferometry [4], but considering an all-integrated approach, where beam combination and modal filtering would be implemented in the same device. This work has been inspired by existing integrated beam combiners devoted to stellar interferometry in near infrared [9].

2. Waveguide fabrication

Since the refractive index $n(x)$ of $\text{AgCl}_x\text{Br}_{1-x}$ for a given wavelength, decreases between $n(0)$ for pure AgBr and $n(1)$ for pure AgCl [10], it is possible to control the refractive index by varying the crystal composition. Two Single crystals of compositions: $\text{AgCl}_{0.28}\text{Br}_{0.72}$ for waveguide material and $\text{AgCl}_{0.3}\text{Br}_{0.7}$ for substrate material, were grown from the melt by the standard Bridgman-Stockbarger technique, using pure starting materials. The crystals were 150 mm long and had a diameter of 10 mm.

A planar plate was cut from each crystal: 8 mm thick and 7.65 mm wide from the $\text{AgCl}_{0.3}\text{Br}_{0.7}$ crystal and an 8 mm thick and 0.35 mm wide from the $\text{AgCl}_{0.28}\text{Br}_{0.72}$ crystal. The two plates were polished, pressed together, heated up and extruded through a small rectangular die, to form a planar waveguide. Three planar waveguides were obtained using this procedure, although the subsequent measurements were only made in one of the samples. The extrusion process and waveguide dimensions are presented in Fig. 1. The thickness of the extruded waveguide layer was $d = 43 \mu\text{m} \pm 2\mu\text{m}$ while the total thickness of the sample was $h = 1.1 \text{ mm}$, both measured with an optical microscope. The sample length was $L = 27.46\text{mm}$ and width $w = 7.5\text{mm}$.

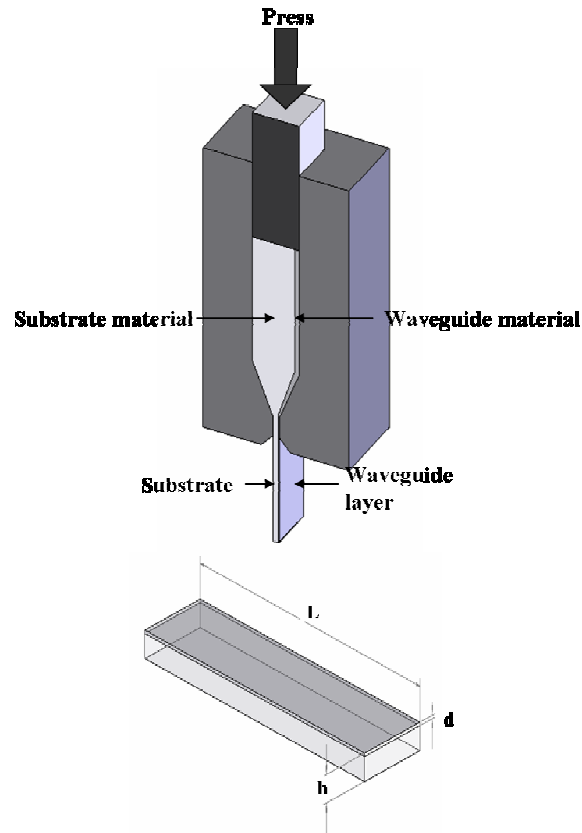


Fig. 1. Upper part: The Extrusion of a planar waveguide. Lower part: The extruded waveguide layer is $d = 43 \mu\text{m} \pm 2\mu\text{m}$ thick while the total thickness of the sample is $h = 1.1 \text{ mm}$.

The refractive indices of substrate ($\text{AgCl}_{0.3}\text{Br}_{0.7}$) and waveguide ($\text{AgCl}_{0.28}\text{Br}_{0.72}$) were measured at $\lambda = 10.6\mu\text{m}$ using an interferometric technique, with high accuracy (± 0.0025). Since the values for the refractive indices were also measured at different wavelengths [10], we were therefore able to deduce a Cauchy-like dependence of the refractive index on the wavelength:

$$n_{\text{AgCl}_{0.3}\text{Br}_{0.7}}(\lambda) = 2.10914 + \frac{0.09665}{\lambda^2} - \frac{0.02413}{\lambda^4} \quad (1)$$

3. Expected guided modes

Using expression (1) for the refractive index of the substrate, and assuming that the waveguide follows the same dispersion law, except for the higher value on the wavelength-independent term, i.e. adding $\Delta n = 0.005$ to Eq. (1), we were able to calculate the theoretical number of guided modes as a function of wavelength. These theoretical values were obtained by solving the transverse resonance condition of the step index planar waveguides (see Eq. (2), taking into account the uncertainties in the refractive indices (0.0025) and in the thickness ($2\mu\text{m}$):

$$k_0 n_g d \cos \theta_m - \phi_s - \phi_c = m\pi \quad (2)$$

where $k_0 = 2\pi/\lambda$ is the wavevector and m an integer. The phase terms at the interface between the waveguide and the substrate (ϕ_s) or the upper-cladding (ϕ_c) are given by:

$$\phi_{s,c} = \arctan \left[\left(\frac{n_g}{n_{s,c}} \right)^{2\rho} \sqrt{\frac{n_g^2 \sin^2 \theta_m - n_{s,c}^2}{n_g^2 - n_g^2 \sin^2 \theta_m}} \right] \quad (3)$$

In this equation n_g , n_s and n_c represent the indices of the waveguide, $n_g = n(\text{AgCl}_{0.28}\text{Br}_{0.72})$, the substrate $n_s = n(\text{AgCl}_{0.3}\text{Br}_{0.7})$, and the upper-cladding $n_c = 1$ respectively. In Eq. (3), ρ represents the polarization of the propagated beam: either TE ($\rho = 0$) or TM ($\rho = 1$). Solving Eq. (2) means to find the set of angles θ_m , which give the effective mode indices $N = n_g \sin \theta_m$ for each m value.

Solving Eq. (2) numerically, the single-mode cut-off wavelength for the TE polarization was found to be $8.465\mu\text{m} \pm 0.390\mu\text{m}$ and this fundamental mode was expected to guide up to a wavelength of $26.1\mu\text{m}$, as shown in Fig. 2. It should be noticed that this upper value was obtained using a simulation, which assumed the nominal transparency of a silver halide crystal. This means that a single-mode operation range of about $18\mu\text{m}$, should be observed in one band. These promising values are in good agreement with the requirements of transparency and single-mode operation range required for space borne interferometers dedicated to extrasolar planet detection (TPF-NASA and Darwin-ESA projects) [11,12].

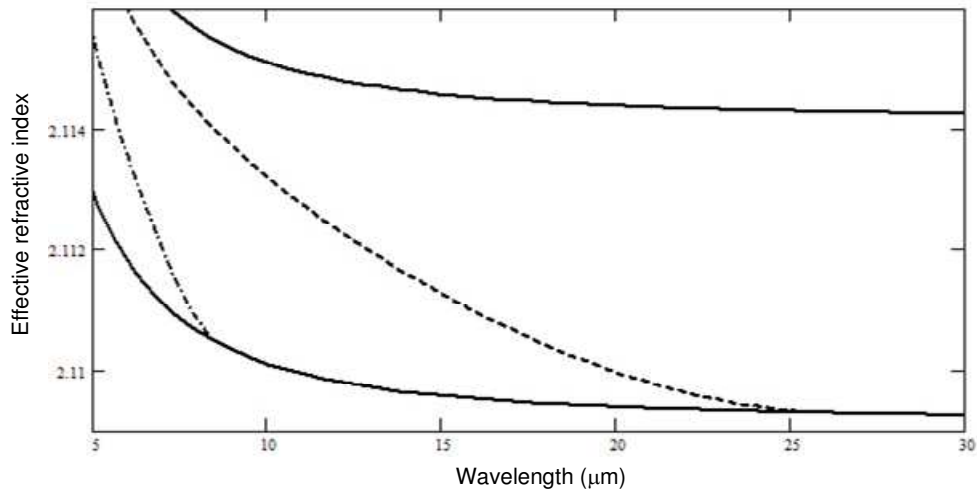


Fig. 2. The theoretical expected values for the effective refractive indices of the step-index planar waveguide. The upper and lower continuous lines represent the guiding limits ($k_0 n_g(\lambda)$ and $k_0 n_s(\lambda)$ respectively). The dashed line is the solution for fundamental mode ($m = 0$) and the dotted line is the solution for the first order ($m = 1$). Intersection of the dashed (resp. dotted) line with the lower continuous line gives the upper (resp. lower) wavelength of the single mode range.

4. Experimental characterization: Fourier Transform Spectroscopy

In order to validate the theoretically expected values, the mid-IR transmission of the waveguide was studied using a Fourier Transform Spectroscopy (FTS) setup.

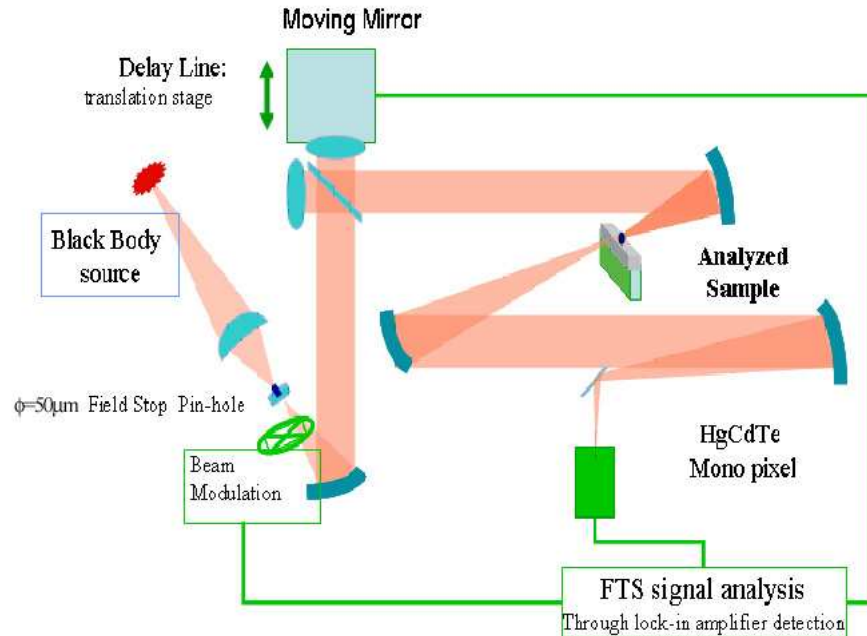


Fig. 3. The experimental set-up of the Fourier Transform Spectrometer

The experimental set-up, shown in Fig. 3, was used to compare the transmission of the bulk substrate to that of the planar waveguide. The blackbody source used emitted a spectrally wide spectrum with a peak emission at $6.5\mu\text{m}$ (i.e. an equivalent temperature of 446K). The emitted radiation was focused into a $50\mu\text{m}$ diameter pinhole and was re-imaged 1:1 using an off-axis parabolic mirror. The diameter of the pinhole that limits the effective black-body area of emission was chosen so it would match as accurately as possible the physical dimensions of the waveguide ($d = 43\mu\text{m}$). The collimated beam was then sent to a beam splitter: 50% was transmitted to a fixed length arm and the other 50% was sent to an optical delay line (moving mirror). Scanning the moving mirror over 2mm, with up to 8192 samples, allows to reach a resolution of 2.5 cm^{-1} (ca. 6nm at $\lambda = 5\mu\text{m}$). After reflection by the mirrors, the signal leaving the interferometer was focused on the sample input. Light intensity propagated through the planar waveguide and emerging from the sample output was re-imaged with 1:1 enlargement using two off-axis parabolic mirrors onto a HgCdTe monapixel detector (IRAssociates, spectral range $3\text{-}13\mu\text{m}$, sensitive area $50\mu\text{m}\times 50\mu\text{m}$). A chopper was used together with a lock-in amplifier in order to improve the signal to noise ratio. The obtained spectra are shown in Fig. 4:

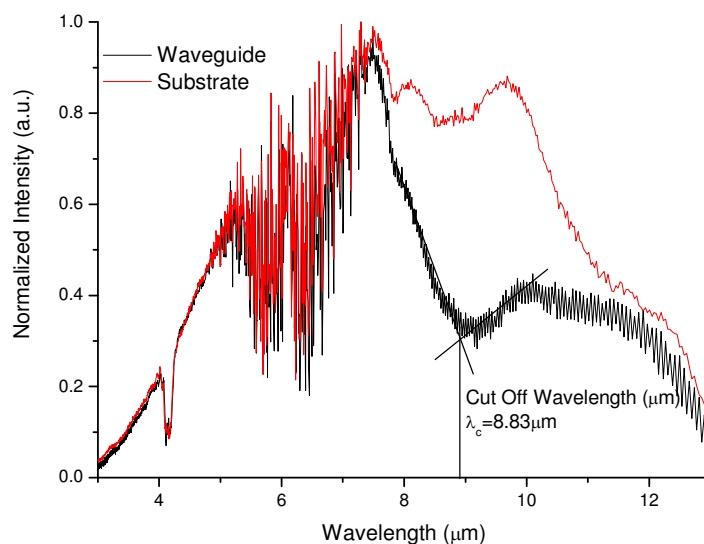


Fig. 4. The normalized FTS spectra obtained for the signal propagated through the substrate, compared to the signal propagated through the waveguide. A drop in intensity is clearly visible around $9\mu\text{m}$, which is the signature of the cut-off wavelength, obtained for a non polarized measurement. Note that the drop in intensity towards $3\mu\text{m}$ (resp. $13\mu\text{m}$) is due to the sensitivity limit of the detector.

In this figure, some features are not related to the waveguide and must be ignored: the water absorption lines observed at $4.2\mu\text{m}$ and in the range from 5 to $7\mu\text{m}$. Figure 4 shows clearly a drop in intensity due to the modal behavior of transmission in the core of the waveguide, as compared to the bulk of the substrate. Indeed, the transmission of the waveguide as a function of wavelength presents sharp drops every time a guided mode is “lost” [13], so that we can deduce the experimental cut-off wavelength which, in the present case, is about $8.83\mu\text{m}$. This value is in good agreement with the theoretically expected one, which is $8.46 \pm 0.39\mu\text{m}$ for the TE fundamental mode, considering the uncertainty on the waveguide thickness.

A set of spectra were recorded using different polarization states of the beam but no significant modification of the cut-off wavelength was obtained. This allows us to conclude that during the planar waveguide fabrication, no particular stress was introduced, that could have distorted the isotropy of the material. In fact, for an isotropic material, the TE and TM cut-off wavelengths were expected at $8.36\mu\text{m}$ for TM and $8.46\mu\text{m}$ for TE, that is, inside the uncertainty range of the measurement discussed before (influence of the waveguide thickness uncertainty on the cut-off wavelength value).

5. Conclusion and perspectives

In conclusion, we have obtained, for the first time to the best of our knowledge, a step-index asymmetric planar waveguide exhibiting a single mode behaviour from $8.83\mu\text{m}$ up to $26.1\mu\text{m}$ (note that the detector limits the measurements to wavelengths shorter than $13\mu\text{m}$). The modal behaviour of the waveguide was studied using a FTS bench adapted for end-fire coupling, showing an intensity drop at the cut-off wavelength. These waveguides are thus adapted to achieve modal filtering in the spectral range of interest for TPF/Darwin missions (6 - $20\mu\text{m}$), with reasonable transparency. Current work is devoted to measure the transmission losses of these waveguides and develop channel waveguides and Y-junctions, in order to realize integrated interferometers and beam combiners. Two different approaches are under study:

photo-induced birefringence using a laser source emitting in the absorption range of the silver halide, and moulding techniques in order to imprint mechanically the channel structure in a soft substrate.

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