Fresnel Lenses: study and fabrication in silicon technology for medium-IR applications

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Introduction:

Infrared optical gas sensors are based on the attenuation of the incident radiation in specific gas absorption bands. The quantity of radiation absorbed depends on the length of the optical path, the gas concentration in the medium, and the absorption coefficient, which is a function of the wavelength and depends on the gas under test. Usually, optical gas sensors are composed by an IR emitter, a gas cell where the gas under test flows and an infrared detector where the remaining radiation is evaluated.

In order to improve the global efficiency of the system, a lens is added to focus the maximum radiation onto the detector increasing the sensor signal.

We are currently involved in the fabrication of a miniaturised infrared gas system, in which as many components as possible are fabricated using silicon microsystems technology. This also applies to the discussed lens for which a Fresnel lens approach has been chosen: diffractive lenses are compatible with the planar nature of silicon microtechnology and, moreover, silicon is transparent in the interested IR range

A Fresnel lens consist of a series of concentric rings with a given tapered shape and whose width gets smaller the further they extend from the lens centre. The topographical lens design is firstly conditioned by the wavelength of the radiation it should focus: the rings shape is governed by the refraction index of the material chosen and the working wavelength in such a way that all ring points introduce a change of optical path that produces a constructive interference at the lens focal point. In our application the working wavelength is fixed by the absorption band of the required gas. The study is carried out for a wavelength of 10.3um (ethylene band absorption) and for 3.4um (many hydrocarbons band absorption, i.e. 3.46um for ethanol and 3.64um for acetaldehyde).

Once the wavelength is fixed, two other parameters determine the lens design: the lens diameter and the focal length. The package that will contain the detector define those parameters. For the proposed detector package (TO5), the needed focal length is f=4mm and its diameter is D=5mm. So, a low focal number lens must be designed. Anyway, some lenses with larger focal length have also been designed.

Technological constrains:

Due to technological constraints, it is necessary to reproduce the theoretical rings profile as a discrete number of flat steps. The fabrication of such a lens would in principle require the combination of photolithographic processes for spatially defining each step and Reactive Ion Etching processes to give each step its proper depth. Obviously, the more numerous the quantization steps, the more efficient the lens will be. However, cost and process complexity limit the number of photolithographic masks which can be used.

The more cost effective way to face this situation is to binary combine *m* photographical levels, chose for each one the proper etch depth and achieve $N=2^m$ quantization steps evenly distributed in depth for each ring.

As it has been said before, the concentric rings (and their internal flat steps) are more closely packed when they are away from the centre of the lens. Technological constraints when using contact photolithography tools limit the minimum feature size to 2-3 microns. This implies that for the topographically more demanding designs (smaller wavelengths, shorter focal lengths) the outer rings cannot meet this criterion and the number of steps must be reduced and the lens efficiency will decrease.

A theoretical study about the global lens efficiency as a function of the lens diameter, the wavelength, the focal length, the minimum feature size, and the number of available steps to reproduce the ideal lens profile has been carried out.

First fabricated lenses:

Binary Fresnel Lenses (BFL) have been fabricated in silicon as a first prototype. This kind of lenses have only two different levels (up and down), so only one photolithographic mask is needed.

Several lenses have been designed for 3.4um and 10.3um wavelengths: 0.4, 1, 2, 5 and 10cm focal length and 4 and 8mm diameter. For each of those lenses, the proper photolithographic mask has been designed. The obtained lens profile has been measured using a confocal microscope.

A coarse wavelength and focal length test has been first carried out inserting the fabricated BFLs in the sample compartment of a Fourier Transform Infrared (FTIR) spectrometer. If a lens is inserted in the IR radiation beam, the radiation is focused to a certain point, and the amount of radiation which reaches on the detector changes. Comparing the FTIR spectrum of a silicon reference with the one of an inserted BFL, the lens effect can be tested. The difference between both spectra can be understood as a qualitative measure of the lens focalization. An evident effect, whose magnitude depended on the lens focal length, was detected in the FTIR spectra of the different BFL lenses around the wavelength those lenses were designed for (and around the multiples of such wavelength that correspond to the different focal planes of a Fresnel Lens).

A direct measurement of the focal length has also been carried out. The global set-up is based on a parallel IR beam, which impinges on the Fresnel Lens, and then on an IR detector, which collects the transmitted radiation.

The source is a quantum cascade laser, with an emission line at 10.3um. It is pulsed with a frequency of 2 KHz and a pulse length of 100ns. The IR detector is a pyrodetector, with a sensitive area of 2mmx2mm. In order to decrease the sensitive area of the detector, a 100um diameter pinhole is glued in front of the pyrodetector. The smaller the effective sensitive area of the detector, the larger the sensitivity of the global set-up is. Using a small pinhole, the situation which the radiation is not exactly focused on the detector but all the radiation falls onto it can be avoided. The nature of a pyrodetector demands a pulsed or chopped source. The pyrodetector output is then acquired by a lock-in amplifier.

The detector is placed on a slider, which allows getting very little movements through the axis. Once the set-up is correctly aligned, the focal length can be measured moving the detector through the axis. When the radiation on the detector reaches a maximum, the distance from the pinhole to the lens is the focal length.

Measured focal lengths successfully fit to the designed focal lengths.

Another important lens parameter is the spot size at the focal plane. After the beam has gone through the lens, it can be considered as a Gaussian beam. In that case the spot size is defined as the region where the irradiance is greater than $1/e^2$ times the center value.

The spot size has been estimated from the collected radiation on the detector through the focal plane. The previous set-up has been modified: the detector has been placed on an x-y sliders. Once the focal plane is found, the pattern radiation is measured moving the detector in a 2D plane with 15um steps in x and y directions. Each measurement is the sum of the irradiance of all the points which are inside the 100um diameter pinhole, so the obtained pattern is smoothed and a numeric treatment is necessary in order to subtract the overlap between measurements.

If the beam is considered as a Gaussian beam at the focal plane, the standard deviation can be estimated from the integration of the points which lights the detector in each measurement. The estimation obtained for a 1cm focal length and 8mm diameter lens, and 2cm focal length and 4mm diameter lens is a 65um and 78um spot size respectively.

The spot size has also been measured away from the focal plane, in order to check how it increases when the analyzed plane is further to the focal plane.

Multiple reflections:

Due to the high refractive index of silicon there are high reflection losses at the surfaces of the Fresnel lenses. If all possible reflections are considered, the light which can pass through a silicon lens decreases to a maximum transmittance of 0.54.

An alternative to reduce the effect of the internal reflections is the use of antireflection coatings. A proper antireflection coating for a 10.3µm wavelength is still being pursued. Typical silicon related materials such as SiO_2 or Si_3N_4 are not good candidates because they unfortunately exhibit important absorption lines close to that wavelength (at 9.4um and 11.8um respectively). The absorption of coatings of those materials of the required antireflection thickness ($\lambda/4n$) is so significant in the 10.3µm region that it renders the lenses opaque at that particular wavelength.

Another alternative to decrease the multiple reflection losses is to design the lens on another substrate, with a lower refraction index. Some polymer substrates, such as PMMA (polymethyl methacrylate), SU8 and PDMS (polydimethyl siloxan) have been considered for that purpose. Anyway, this kind of polymers also shows some drawbacks: they are not as rigid as silicon and their optical performance can be temperature dependent. The lens should be able to work in a wide temperature range, so the refraction index has to be stable in all the working temperature range.

Eight levels lenses:

In order to increase the lens efficiency, some Fresnel Lenses have been designed and fabricated in silicon using three photolithographic masks levels, i.e. an eight steps quantization can be achieved. The lens profile has been measured using a confocal microscope showing that with the proper etch associated to each mask level (*d*, 2*d*, 4*d* etch depths) up to eight equally spaced steps are obtained with the three photolithographic masks.

Using Hot Embossing Lithgraphy, some lenses (a Binary Fresnel Lens and eight levels Fresnel Lens) have been stamped on PMMA polymer, in order to test the reproducibility of the process. The obtained profile is the opposite of the lens used as a master. Some of the features are a little bit tall, because of some sticking of the polymer to the master. This problem is much more evident in the lens outer zones.

Conclusions:

A theoretical study about the Fresnel Lens efficiency as a function of the number of photolithographic masks and the minimum feature size has been done. It has been shown how to change the lens design when the technological constraints force to decrease the number of quantization steps. The alternative based on a binary combination of up to three masks has been chosen because it is technologically amenable, cost effective, and the resulting efficiency does not decrease dramatically.

The device fabrication has been successfully carried out and the first optical tests have been performed. The measured focal length fits with the designed and the transmittance increases when going from one to eight quantization steps.

Anyway, some alternatives are still considered, in order to decrease the effect of internal reflections. With that purpose, antireflection coatings and some polymers materials have to be studied more accurately.

The work should finish with a lens able to work in real conditions, as an element in an infrared optical gas sensor.