Optically Controlled Quasi-Optical Local Oscillator Injection for a 100 GHz SIS Imaging Receiver

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***Abstract*—We present a novel approach to the problem of quasi-optical LO injection in a 100 GHz SIS imaging receiver. The use of a specially engineered molecular beam epitaxy material as an all-optical millimeter wave modulator is presented. This optically controlled modulator, used together with a kinoform to generate and control an array of Gaussian beams, is an efficient, completely solid-state, rugged and physically small solution. The working principle of the optically controlled modulator lies in the fact that the conductivity of a semiconductor can be changed by the generation of free carriers under photonic excitation, thus changing its refractive index.**

I. Introduction

The advent of the superconductor-insulator-superconductor mixer (SIS) during the last decade has given a dramatic increase in the sensitivity of the heterodyne receivers used in radioastronomy. During the next decade we expect to see a further increase in the efficiency of the use of radio telescopes through the installation of imaging systems [1]–[3].

The idea of an imaging receiver being basically the introduction of an array of mixers at the focal plane of the telescope in order to cover an spatially extended area of the sky during each observation.

The Department of Radio and Space Science at Chalmers University of Technology, Gothenburg, Sweden, is currently developing a 100 GHz 4 × 4 SIS mixer imaging receiver, named SISYFOS,[1] to be installed in the 20 m diameter telescope at the National Facility of Onsala Space Observatory, Sweden [2].

The technology for the design and manufacture of these mixers has become quite mature and all major millimeter wave radiotelescopes are equipped with receivers of this type. Nevertheless, there are drawbacks: they need cooling to 4 K, they can suffer from a limited dynamic range, instabilities, and are rather sensitive to the actual power of the local oscillator signal (LO). As advantages, together with noise temperatures approaching the quantum limit, it can be mentioned that they are mechanically more rugged that the Schottky diode type mixer and that they need very low LO power, of the order of nW.

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[1] SIS Imaging System for Onsala Space Observatory or, alternatively, in Greek Mythology the shrewd and greedy king of Corinth who was doomed forever in Hades to roll uphill a heavy stone which kept rolling down again.

This paper deals with a solution for quasi-optical injection of the LO signal on an imaging receiver where, by using diffractive optics, an array of Gaussian beams is generated [7]. Later we use a material that, through photonic interaction, achieves optically controlled spatial modulation of the millimeter wave signal propagating through it. These two quasi-optical components seem very promising to solve not only this particular problem of LO injection to an SIS mixer array, but many other quasi-optical power control problems encountered in (sub-) millimeter wave technology [4]–[6], [8].

II. Quasi-Optical Injection: Alternatives

In order to distribute efficiently the out-coming Gaussian beam from a (sub-) millimeter wave source the most attractive method seems to be the use of a kinoform to produce a predefined output pattern by means of phase interference. This approach, rather novel at these frequencies, has been reported to be practical at 100 GHz with efficiencies close to 95% [7].

The next questions to answer is, what method should we use to quasi-optically modulate the individual beams? If we consider only solutions not involving mechanical tuning, we have three main approaches

- Active grids.
- Ferrimagnetic devices.
- Semiconductor devices.

While all three solutions are feasible to some extent, we will concentrate ourselves on the last one.

A. Semiconductor Devices

During the late sixties work was started around visible displays for (sub-) millimeter images in the quest for a passive imaging system, mainly for surveillance applications under adverse weather conditions [9]–[11]. During the last years there has been some renewed interest in using the photoelectronic effect for high speed modulation of a far-infrared beam [12].

The principle behind these imaging displays and the far-infrared modulator is the same and is simply the generation of an excess carrier density though photonic stimulation of a slab of semiconductor material. The change in carrier density changes the resistivity of the material, which leads to absorption within the bulk of it and a change of its optical properties.

Very early it was recognized that these bulk semiconductor devices suffered from the limitation of short carrier lifetime and thus they needed high illumination powers in order

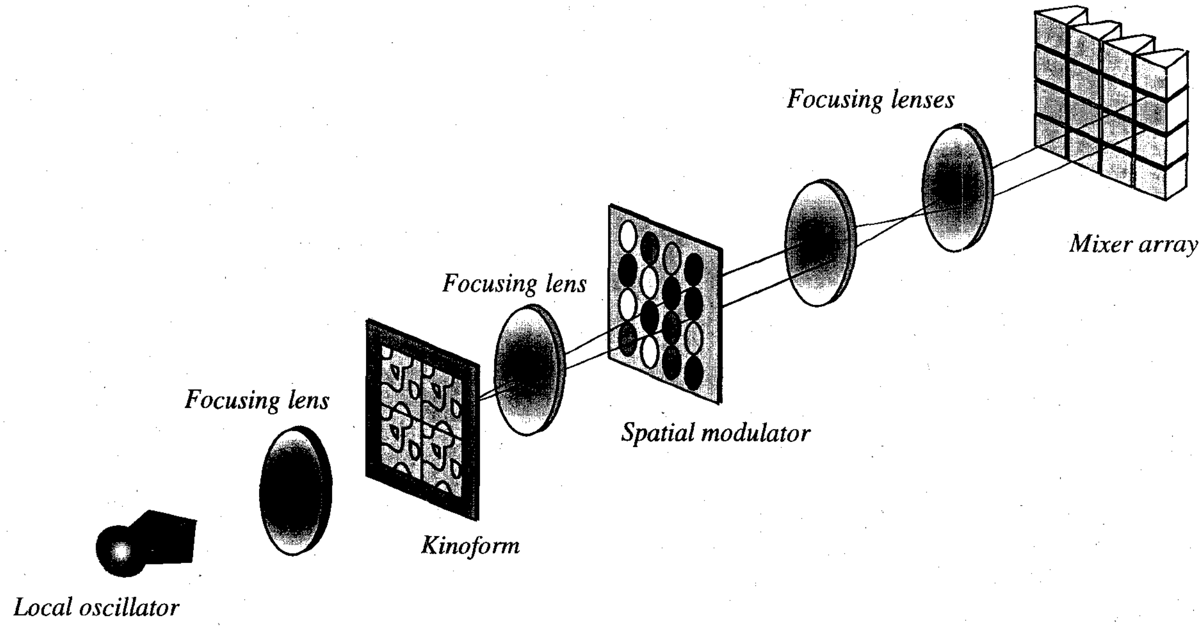

Fig. 1. Scheme of the optically controlled quasi-optical LO injection for an imaging receiver.

to produce some relatively modest modulation [13]. Due to this, better devices employing interferometric techniques where introduced [13] but, in spite of the improvement, the subject of waveguide or quasi-optical control of RF using bulk semiconductors was abandoned until recently. Some of these devices were reviewed in [14].

Nowadays, with the advancement of sophisticated techniques of molecular beam epitaxy (MBE), there exists a plethora of human engineered material. One of these is the InGaAs/GaAs *nipi*-doped multiple quantum well (MQW) structure described by Larsson and Maserjian [15]. This structure has the combined advantages of very long recombination times (of the order of milliseconds), due to the spatial separation of the carriers in the *nipi* structure [16], and thus inherently high optical efficiency (large excess carrier densities can be obtained with a relatively low power optical excitation [17]). This latter effect is enhanced by the addition of quantum well structures in the conduction band minima [18]. We have explored the potential of this material as a optically controlled quasi-optical modulator of a Gaussian beam and the results have been encouraging enough to use this material in the here described LO system [4]–[6], [8].

In practice a quasi-optical modulator based on this *nipi*-doped semiconductor is as simple as passing a (sub-) millimeter wave Gaussian beam through the substrate, isolated from ambient light, and at the same time shine over it the IR control light. By modulating the optical power we can achieve control of the transmitted and reflected RF power [19].

III. Complete System

The system designed is shown schematically in Fig. 1. It is comprised of a local oscillator source, e.g., a Gunn oscillator at 100 $\pm$ 10 GHz. Its output is coupled to a plane-convex lens, with focal length f_1, to create a plane wavefront at the kinoform plane. A second lens is placed at a distance equal to its focal length, f_2, from the kinoform. At a distance f_2 of the lens we have the diffraction or Fourier plane where the desired intensity distribution pattern is located. In this last plane we install the *nipi*-doped MQW elements, one for each beam, with the corresponding individual IR light control sources. Some more optics is required to re-image this individually modulated array of Gaussian beams unto the mixer array.

A. Kinoform

Kinoform is another name for computer generated hologram. They have been studied for two decades at optical wavelengths [20], but recently there have also been reports on the feasibility of using them at millimeter wave frequencies [21], [7]. These devices work by phase modulating an incoming plane wavefront in order to synthesize a desired output pattern. In theory they can be 100% efficient since no absorption is involved as in the case of amplitude modulation (we define efficiency as the fraction of the incident beam power deflected into the prescribed intensity distribution at the image plane). In practice, they show efficiencies close to 95% at mm wavelengths [7].

The fabrication of one of these holograms starts by the specification of the far-field intensity distribution, and through a modified Gerchberg-Saxton algorithm the phase correction to be introduced to the original plane wavefront is obtained [22].

We wanted our kinoform to produce 16 equally intense beams in a 4 $\times$ 4 array in the diffraction plane. We also required it to be binary, i.e., to have only two relief levels, for easy manufacture (0 and π phase correction). For a binary kinoform the resulting diffraction plane amplitude distribution is mirror symmetric about the optical axis thus, to obtain maximum efficiency, the pattern should be symmetrical around this axis. By using this configuration for our 4 $\times$ 4 pattern every desired diffracted beam has also a diffracted image beam symmetric respect the optical axis. By making this latter beam also a part of the array no power is wasted on it. To conclude: we only have to generate eight beams and the other eight will come as "the free lunch."

The final result of the calculations is a phase distribution of the field in the kinoform plane, this can directly be interpreted as a kinoform relief depth because the phase difference $\Delta\phi$ between two points is proportional to the depth Δd

$$\Delta\phi = \frac{2\pi}{\lambda_0}(n-1)\Delta d \tag{1}$$

where n is the refractive index of the kinoform material. In our case we use Teflon as the base material and the surface relief is made just by using a numerically controlled milling machine to mill-out the desired depth.

Using results from Gaussian optics, we obtain that a horn with waist ω_0 placed at the focus of lens #1 will illuminate the kinoform with a beam radius ω_k, provided that the focus satisfies the relation

$$f_1 = z_c\sqrt{\left(\frac{\omega_k}{\omega_0}\right)^2 - 1} \tag{2}$$

where z_{c_1} is the confocal distance.

By selecting the desired illumination taper at the kinoform and imposing that the focal number of the calculated lens should be greater than unity we get all the conditions needed to calculate f_1.

The dimensions of the second lens are chosen by considering that the distance between adjacent beams d, is given as function of the focal length, f_2, by

$$d(f_2) = \frac{2\lambda f_2}{a} \tag{3}$$

where a is the side dimension of the basic kinoform cell.

B. MQW Structure

The material used as the optically controlled RF modulator is an engineered semiconductor heterostructure optimized for optically controlled optical modulation [15]. The structure is grown by MBE, and consists of 44 $In_{0.2}Ga_{0.8}As$ quantum wells (QW), each 6.5 nm thick, separated by 78 nm thick GaAs barriers. In the center of each GaAs barrier a Be-doping plane (p-type) with a sheet density of $9\cdot10^{12}$ cm^{-2} is inserted. On both sides of the QW's, using 10 nm thick spacer layers, Si-doping planes (n-type) with sheet densities of $3\cdot10^{12}$ cm^{-2} are inserted. This results in an excess free hole density under thermal equilibrium.

Under photoinduced electron-hole pair generation electrons will be attracted to the QWs and the holes to the barrier region midway between the wells resulting in their spatial separation, as shown on the scheme of the $nipi$-doped structure on Fig. 2. This spatial separation of the carriers reduces the recombination rate and thus a large increase in the density of free carriers can be established using low optical excitation intensities. This facilitates efficient modulation of (sub-) millimeter waves using low optical control intensities.

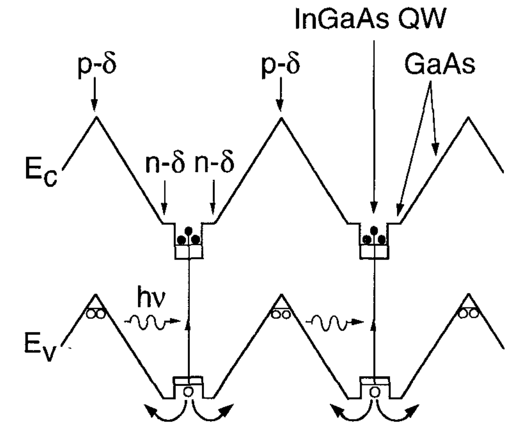

Fig. 2. Energy bands diagram for the periodically doped InGaAs/GaAs MQW sample showing the spatial separation (provided by Prof. Anders Larsson).

The structure has been described elsewhere, as well as its main properties for modulation in the near infrared [15], [16]. Its potential in the (sub-) millimeter wavelength region has also been reported previously [5], [6].

The physical principle behind the millimeter wave modulation is the generation of an excess carrier density through optical excitation. This excess carrier density modifies the conductivity of the semiconductor with a subsequent change in the optical properties. The complex relative permittivity in this case, is given by

$$\tilde{\varepsilon}_r(N_e,\omega) = \varepsilon_r + \omega_p^2\left\langle\frac{\tau_m^2}{1+(\omega\tau_m)^2}\right\rangle - j\frac{\omega_p^2}{\omega}\left\langle\frac{\tau_m}{1+(\omega\tau_m)^2}\right\rangle \tag{4}$$

where ε_r is the relative permittivity of the base material, τ_m the momentum relaxation time, ω the (sub-) millimeter wave angular frequency, and ω_p is the plasma frequency

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e^*}} \tag{5}$$

with N_e the excess carrier density, ε_0 the free space permittivity, e the electron charge, and m_e^* the effective electron mass.

Equation (4) is valid provided that mainly electrons contribute to the conductivity. This is a good approximation in GaAs since the hole mobility is nearly 20 times lower than that for electrons.

Bellow the plasma frequency the photo-modulation of the free carrier density changes the active region from a nearly lossless dielectric into an imperfect mirror. For frequencies above the plasma frequency the imaginary part of the permitivity becomes negligible and the material becomes "transparent."

The $nipi$-doped MQW structure is cut in square pieces, $9\times9\,\text{mm}^2$, housed in a machined block of PVC covered with an IR filter and Teflon at both sides, with anti-reflection coating on the surface of both Teflon covers. The commercial IR light sources (TIL 31B, 6 mW typical output power {@} 100 mA, λ = 940 nm) are housed on the same block and the geometry of them is such as to create a Gaussian light spot with FWHM

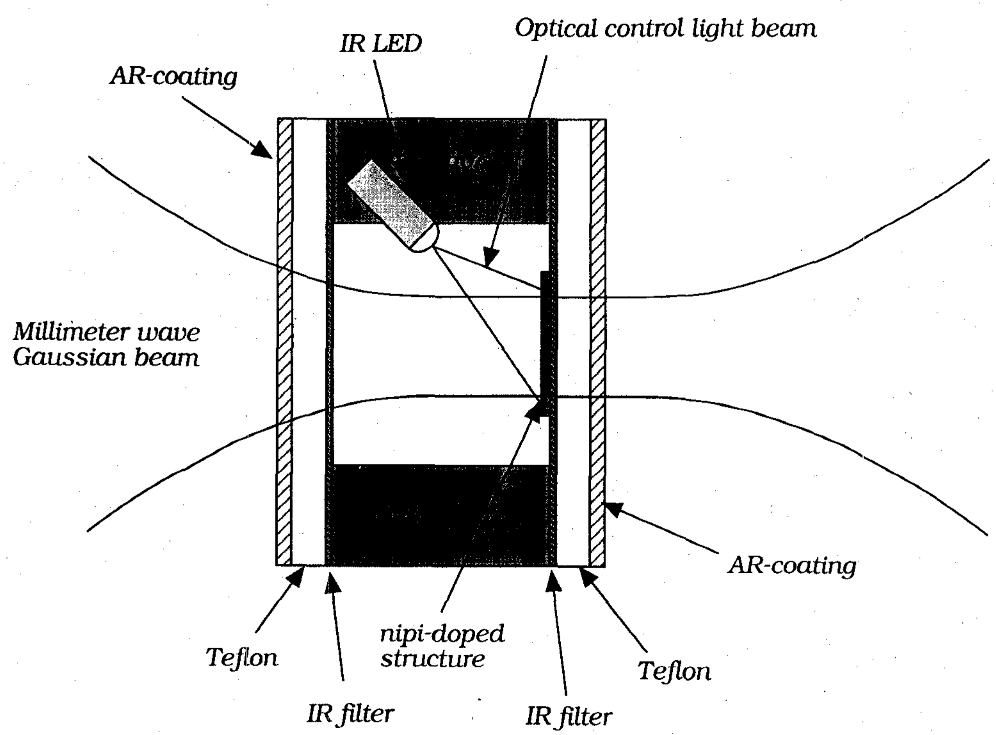

Fig. 3. Schematic lay-out of the housing of one of the optically controlled *nipi*-doped attenuators.

of about 2 mm, yielding a maximum optical intensity on the order of 40 mW/cm^2 for a 100 mA drive current [23]. A simplified diagram of one pixel of the optical modulator is shown in Fig. 3.

We know that the lifetime of the photoinduced carriers on this material is about 80 ms under these illumination conditions [6], [8], [16], and we use this fact to design a technique of multiplexing the IR light diode array in order to use a single low-current power supply: the sixteen digital words, corresponding to the bias current of each one of the diodes on the control matrix, are stored on a RAM and this one is scanned sequentially to, after D/A conversion, be applied to each diode at a frequency of 1 kHz.

The position of the synthesized Gaussian beams is given by (3) and from it we can dimension the center-to-center spacing of the cells of the optical modulator by using the center wavelength over the operating band as the design wavelength.

IV. Results

We measured the power distribution of the synthesized beams at the diffraction plane for different frequencies, this was done for a setup with $f_2 = 196$ mm. The contour map for the center frequency (100 GHz) is shown in Fig. 4. We can see that the array of Gaussian beams is homogeneous and evenly distributed in the pre-defined 4×4 grid. The contour map covers an area of $80 \times 80\,\text{mm}^2$ with a spacing of 2 mm between measured points. They where acquire using a far-field X-Y measurement range under computer control. The RF probe in the X-Y mapper was a chamfered open-end waveguide to provide a small scanning spot with well-known characteristics [24].

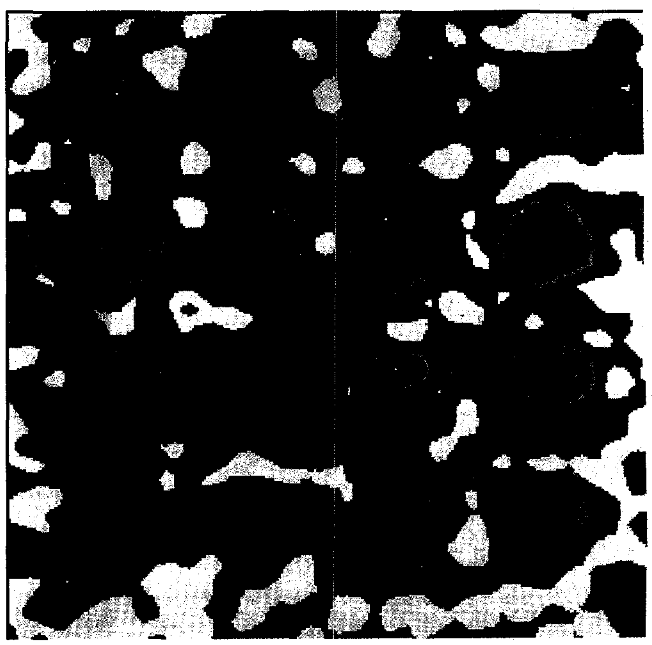

Fig. 4. Contour map at the diffraction plane of the kinoform for 100 GHz. Map size is 80×80 mm$_2$ with a step of 2 mm; contour lines are spaced 1.5 dB.

The measured spread of the power amplitudes between the different peaks is 3.2 dB at 90 GHz, 2.5 dB at 100 GHz, and 2.1 dB at 110 GHz.

Next we replaced the amplitude modulator at the diffraction plane and measured the modulation depth as function of the bias current on the IR light source for four different frequencies: the frequency of the center wavelength over the band, 96 GHz; the center frequency of the band, 100 GHz; and the band edges, 90 and 110 GHz. The result is shown in

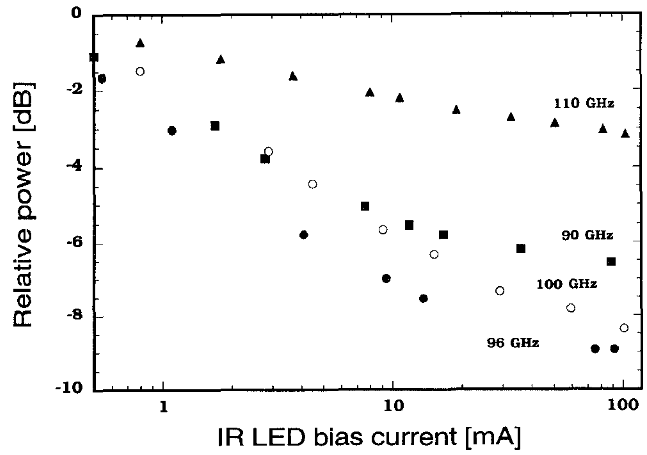

Fig. 5. Modulation depth as function of the bias current on the IR light source for different frequencies.

Fig. 5 where it is possible to see that at the center wavelength, where the optimum design position is, the modulation depth is biggest reaching 9 dB. This performance degrades noticeably towards the band edges to reach a minimum of 3 dB at the higher frequency end. The last result was expected due to the displacement of the center of the synthesized Gaussian beams over the *nipi*-doped MQW structure. This effect turns out to be more severe at the high frequency side because the beam is narrower at higher frequencies and the fixed geometry of the IR light source, used to control the power transmission, creates a small active area on the *nipi*-doped structure with a rapid decay due to the short diffusion length of the photo-generated carrier density on it: the diffusion length of the carriers under the same illumination conditions has been determined to be of the order of 1 mm [6], [8].

The insertion loss through the modulator, in the absence of IR light, was measured to be 7 dB averaged over the different beams.

V. Discussion and Conclusions

We have designed, built and tested a novel scheme for the quasi-optical LO injection of an imaging receiver. Measurements of the system have been performed, showing that it works as expected: we have achieved spatial distribution of a single LO source unto a grid of equi-spaced Gaussian beams and also quasi-optical power control of these.

The configuration is extremely simple and has no mechanical moving parts subject to wear. Besides, the fact of being completely solid state makes it ideal to be used in the harsh environment of a radio-telescope.

Due to the diffractive nature of the array of Gaussian beams generated by the kinoform, we have a frequency dependence on the spacing between them that impairs the good photoinduced modulation capabilities of the *nipi*-doped MQW structure.

One way to overcome this last problem can be the use of an IR light source with a broader illumination beam. The decrease of the focal length of the second lens is also a viable solution to improve the performance, since we will have a smaller range for the beam separation over the operating band, as indicated by (3). Another alternative is to mechanically move the second lens to compensate for the beam separation, though this will add a quadratic phase change over the kinoform image.

The principle of this design can be scaled without problems to higher frequencies where we expect the kinoform to have better performance due to the possibility of having a bigger interaction area (in terms of the area of the basic cell) and thus a better resolution for the individual beams [8]. We have shown before that the *nipi*-doped structure performs well up to frequencies of the order of 2 THz provided that we are prepared to accept losses of the order of 6 dB due to insertion loss on the material [5], [6].

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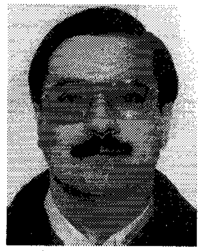

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