Reflective grating-coupled structure improves the detection efficiency of THz array detectors

Peng Xiao, Xuecou Tu, Lin Kang, Chengtao Jiang, Shimin Zhai, Zhou Jiang, Danfeng Pan, Jian Chen, Xiaoqing Jia & Peiheng Wu

A reflective grating-coupled structure on the silicon substrate was designed to improve the detection efficiency of terahertz detectors for the frequency ranging from 0.26 THz to 0.36 THz. By using finite difference time domain (FDTD) solutions, the simulation and optimized design of the grating-coupled structure were carried out. The results showed that the signal was effectively reflected and diffracted by the reflective grating-coupled structure which significantly enhanced the electric field in the place of the detector. The maximum electric field can be increased by 2.8 times than that of the Fabry-Perot resonator. To verify the design results, the reflective grating-coupled structure was applied in the preparation of the Nb$_3$N$_6$ array detector chip and compared with the Nb$_3$N$_6$ array detector chip with the F-P resonator. The results showed that the maximum voltage responsivity of the Nb$_3$N$_6$ detector with the reflective grating-coupled structure was 2 times larger than the Nb$_3$N$_6$ detector with the F-P resonator. It indicates that the reflective grating-coupled structure can efficiently improve the detection efficiency of THz detectors.

Terahertz (THz) detectors, which has attracted great attention and been applied in many fields such as security check, medical imaging and components identification, actually play a very important role in the field of the THz (0.1 THz~10 THz) technology. Therefore, it is of great significance to further improve the detection efficiency and sensitivity of the THz detector. In the THz frequency range, the Gaussian beam is usually used to describe the transmission characteristics of the THz wave. Subject to the diffraction limit, the lower bound of the Gaussian beam waist is about $0.9003 \lambda$, in the THz quasi-optical system. That being said, for THz detector prepared by microfabrication, the size of the focused Gaussian beam waist is much larger than that of the detector. Such limitation leads to a low signal coupling efficiency. Therefore, many coupling structures have been applied to improve the signal coupling efficiency of THz detector, for example, the extended hemispherical lens, diffractive lens, F-P air cavity and metal grating coupler, etc. However, the sizes of the extended hemispherical lens and the diffractive lens are much larger than that of the detector. In addition, the preparation processes are complicated and expensive, hence makes it harder to be applied to fabricate large-scale detectors array. The F-P air cavity is used in the infrared band to improve the detection efficiency of the detector, but its effectiveness is limited in THz band. Based in that, some innovative concepts and structures are gradually applied to replace traditional geometric optics in order to eliminate these limitations. For example, flat optics can produce abrupt changes over the scale of the free-space wavelength in the phase, amplitude and polarization of a light beam by assembling arrays of miniature, and anisotropic light scatterers. The size and the period of the unit are much smaller than the wavelength. According to Huygens principle, flat optics can mould optical wavefronts into arbitrary shapes with subwavelength resolution by introducing spatial variations in the optical response of the light scatterers. Therefore, it can create smaller and more optically efficient products, and at the same time, are also gradually used in THz band. The detection efficiency can be improved by using the sub-wavelength periodic structure to regulate the phase and amplitude of the signal.

In this paper, a reflective grating-coupled structure with sub-wavelength size and high coupling efficiency was designed and fabricated for Nb$_3$N$_6$ array detector. The experimental results verified that with the reflective grating-coupled structure, the maximum voltage responsivity of Nb$_3$N$_6$ array detector was 2 times larger than that of detectors array with a F-P resonator.

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Design and Results
To improve the detection efficiency of the THz array detector, a reflective grating-coupled structure on the basis of the F-P resonator was designed, i.e. a grating structure with a certain width and depth is attached to the back of Si substrate, and it is covered by a 200 nm-thick Au film, as shown in Fig. 1.

Here, \( H \) is the substrate thickness, \( d \) is the height of the grating, \( L (L = H - d) \) is the height of the grating gear, \( W \) is the width of the grating gear, \( W_0 \) is the width of the groove and \( P (P = W + W_0) \) is the grating period. The red area indicates the place of the THz array detector. The blue dotted line is the centerline of the grating period; the \( O_1 \) and \( O_2 \) are the center point of the grating gear and detector, respectively. For the reflective grating-coupled structure, a portion of the incidence signal is reflected at the substrate surface, and the resident signals transmit into the silicon substrate. The transmission signals at the grating gear place can be totally reflected, which is similar to the case of F-P cavity. Besides, the transmission signals at the groove place can be diffracted due to the grating effect. So the reflected and diffracted signals in substrate could be effectively coupled to the substrate surface, and the signals in the place of the detector can be enhanced if their phases are equivalent. The reflective grating-coupled structure makes the signal in the place of the detector larger compared with the F-P cavity.

The simulation design of the reflective grating-coupled structure is performed by using FDTD software (FDTD Solutions, Lumerical Inc.) in a two-dimensional (2D) system—the X-Y plane in Fig. 1. Because of the periodic condition of the reflective grating-coupled structure, the simulated object is a unit cell (shown as a green dotted rectangle in Fig. 1), which has periodic boundary conditions (PBC) on its left and right boundaries and perfect matched layer (PML) conditions on its top and bottom boundaries. In the simulations, a polarized plane wave with the electric (E) field amplitude of 1 V/m, propagates along the Y-axis, is employed as the incident signal \( (\alpha = 0^\circ) \). The grid size is set to 1 \( \mu \)m which is much smaller than the unit sizes and the operating wavelength.

According to the simulation and optimized design results, a group of optimized parameters \( H = 500 \mu \)m, \( L = 15 \mu \)m, \( W_0 = 100 \mu \)m, and \( P = 400 \mu \)m are selected. Figure 2(a) presents a frequency dependence of the E field along the X-axis on the Si substrate surface. (b) \( E^2 \) distribution on the cross-section of the substrate in a periodic unit cell at 0.318 THz.

**Figure 1.** The cross-section of the reflective grating-coupled structure. The red area indicates the place of the detector, the blue dotted line is the centerline of a periodic unit cell (P).

**Figure 2.** Simulated focusing characteristics, when \( H = 500 \mu \)m, \( L = 15 \mu \)m, \( W_0 = 100 \mu \)m, and \( P = 400 \mu \)m.
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To verify the design results, based on the optimal parameters, the reflective grating-coupled structure was applied in the preparation of the Nb$_5$N$_6$ array detector. Nb$_5$N$_6$ detector mainly consists of a gold dipole planar antenna and Nb$_5$N$_6$ thin film microbridge as shown in Fig. 3(b). When the detector is irradiated by THz waves, the signal can be received by the dipole antenna and coupled to the Nb$_5$N$_6$ microbridge. After receiving the energy from the irradiated power, the resistance of the detector changes with the Joule heating. By applying a bias current to the detector, the change in resistance can be converted to a voltage change.

And the measured results are compared with Nb$_5$N$_6$ array detector integrated with a F-P resonator, which has a maximum responsivity of 580 V/W$^{\text{21}}$. The optimization parameters of the reflective grating-coupled structure are shown in Fig. 3(c). The Si substrate thickness $H$ is 500 $\mu$m, the grating period $P$ is 400 $\mu$m, the height of the grating $d$ is 485 $\mu$m, and the width of grating gear $W$ is 300 $\mu$m. Each grating periodic unit contains an Nb$_5$N$_6$ detector at its surface center. Figure 3(a) is a cross-section SEM picture of the grating groove and Fig. 3(b) shows an optical microscope picture of Nb$_5$N$_6$ array detector chip, respectively.

To facilitate results analysis, the measured voltage responsivity of Nb$_5$N$_6$ array detector with two structures were normalized and compared with the simulated results. For impedance detector integrated with a F-P resonator, a normalized voltage responsivity is shown in Fig. 4(a). The purple solid line is the relations between simulated electric fields and frequency. A maximum value of 1.94 V/m is at 0.318 THz. Here, a 480 $\mu$m-thick silicon wafer is used as the substrate of the F-P resonator to ensure that the resonant frequency lies in the frequency range of 0.315 THz to 0.32 THz. The cyan dotted line is the measured results, with a maximum normalized voltage responsivity of 0.5 at 0.323 THz. Each grating periodic unit contains an Nb$_5$N$_6$ detector at its surface center. Figure 3(a) is a cross-section SEM picture of the grating groove and Fig. 3(b) shows an optical microscope picture of Nb$_5$N$_6$ array detector chip, respectively.

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There is a small shift at the resonance frequencies in Fig. 4. Such deviation could be due to the imperfection when matching between the Nb$_5$N$_6$ microbridge impedance, dipole planar antenna impedance and wave impedance in free space. Thus, this small shift should not be considered as the effect of the size deviation in the fabrication process.

**Discussion**

To ensure the resonant frequency of the reflective grating-coupled structure is between 0.26 THz to 0.36 THz, $H = 500 \mu$m is firstly chosen. To make use of the first order diffraction, the grating period should be smaller than the wavelength in free space, but larger than that in silicon$^{\text{19}}$. Moreover, 400 $\mu$m grating period is chosen based on the detector size, the signal amplitude, the bandwidth and the processing technology. By using FDTD Solutions, the influence of structural parameters on the coupling ability of the reflective grating-coupled structure was investigated. Based on the three parameters, $H = 300 \mu$m, $P = 400 \mu$m and $L = 15 \mu$m, Fig. 5(a) shows the effect of changing $W_0$ from 0 to 125 $\mu$m. It was a F-P resonator when $W_0 = 0 \mu$m, associated with a peak value of 1.97 V/m electric field on the surface of Si substrate. When the $W_0$ was increased to 25 $\mu$m, because of the reflective grating-coupled structure, the electric field in the place of the detector was significantly increased to 9.95 V/m.
(about 5 times comparing to the electric field value of the F-P resonator). But the full width at half maximum (FWHM) of the electric field peak was only 1.25 GHz. Increasing \( W_0 \) from 25 \( \mu \)m to 125 \( \mu \)m, the electric field peak gradually decreased with the bandwidth gradually increased. At the value of 125 \( \mu \)m, the electric field peak was reduced to 4.95 V/m, but the FWHM of the electric field peak risen to 8 GHz.

At the value of \( W_0 = 100 \mu \)m, an optimal combination of a relatively high electric field (5.6 V/m) and proper bandwidth (6 GHz) would be achieved. Thus, Fig. 5(b) shows the results using parameters \( H = 500 \mu \)m, \( P = 400 \mu \)m, \( W_0 = 100 \mu \)m, \( L = 0 \sim 45 \mu \)m. When \( L \) was increased to 10 \( \mu \)m, the electric field in the place of the detector was significantly enhanced and the maximum value reached up to 6.6 V/m, the FWHM of the electric field peak was 4 GHz. When \( L \) was 15 \( \mu \)m, the electric field peak was reduced to 5.6 V/m, but the FWHM of the electric field peak increased to 6 GHz. No significant change was found in field peak and bandwidth if further increasing \( L \).

**Figure 4.** (a) The cyan dotted line shows the normalized voltage responsivity of the Nb 5N6 detector with the F-P resonator. The purple solid line shows the simulated value of \( E_x = 0, y = 480 \) on the F-P resonator. (b) The blue dotted line shows the normalized voltage responsivity of the Nb 5N6 detector with the reflective grating-coupled structure. The green solid line shows the simulated value of \( E_x = 0, y = 500 \) on the reflective grating-coupled structure.

**Figure 5.** The relations between different frequencies and the \( E \) field in the place of the detector under different parameters: (a) \( H = 500 \mu \)m, \( L = 15 \mu \)m, \( P = 400 \mu \)m, \( W_0 = 0 \sim 125 \mu \)m; (b) \( H = 500 \mu \)m, \( P = 400 \mu \)m, \( W_0 = 100 \mu \)m, \( L = 0 \sim 45 \mu \)m; (c) \( H = 500 \mu \)m, \( L = 15 \mu \)m, \( W_0 = 100 \mu \)m, \( P = 390 \sim 420 \mu \)m.
At last, the results of changing the grating period \((P)\) are shown in Fig. 5(c), when \(H = 500 \mu\text{m}, \ L = 15 \mu\text{m}\) and \(W_0 = 100 \mu\text{m}\). Similar as before, \(L = 15 \mu\text{m}\) was chosen because an relatively optimal combination can be achieved. Increasing \(P\) from 390 \(\mu\text{m}\) to 420 \(\mu\text{m}\), the electric field peak shifted towards the direction of the lower frequency. In other words, the peak values decreased from 6.38 V/m to 4.76 V/m and the resonant frequency changed from 0.32 THz to 0.308 THz, corresponding to \(P\) from 390 \(\mu\text{m}\) to 420 \(\mu\text{m}\).

According to above simulation analyses, a group of optimized structural parameters are confirmed finally, i.e. \(H = 500 \mu\text{m}, \ L = 15 \mu\text{m}, \ W_0 = 100 \mu\text{m}\) and \(P = 400 \mu\text{m}\). On the basis of the optimized structure, we studied the influence of different incident angles \((\alpha)\) on the normalized \(E^2\) in the place of the detector as shown in Fig. 6. The \(E^2\) amplitude gradually increased when changing \(\alpha\) from \(-90^\circ\) to \(0^\circ\), the maximum normalized \(E^2\) is 1 when \(\alpha = 0^\circ\). And when increasing \(\alpha\) from \(0^\circ\) to \(90^\circ\), the \(E^2\) amplitude gradually decreased as shown in Fig. 6. Due to the nonzero electric field component in case of oblique incidence, which propagates along the X-axis, unable to be diffracted or reflected by the reflective grating-coupled structure. So, it makes the \(E^2\) amplitude in case of oblique incidence \((\alpha \neq 0)\) smaller than that case of normal incidence \((\alpha = 0)\).

**Methods**

**Reflective grating-coupled structure.** In the design of THz array detector chip, different kinds of structures are usually added on the substrate to enhance the detection efficiency. A metallic layer is deposited on the back of the substrate to make up a metallic Fabry-Perot (F-P) cavity. The incident signal can be enhanced on the substrate surface if the substrate thickness (i.e. F-P cavity) and the wavelength satisfy Eq. (1):

\[
2nH = (2k_1 - 1)\frac{\lambda}{2}, \ (k_1 = 1, 2, 3, \cdots).
\]

where \(n\) and \(H\) are the refractive index \((n = 3.45\ \text{for Si})\) and the substrate thickness respectively.

For this current reflective grating-coupled structure, the incident signal could be focused on the substrate surface highly effectively by the reflection and diffraction effects. The transmission signals at the grating gear place can be totally reflected, which is similar to the case of F-P cavity. Besides, the transmission signals at the groove place can be diffracted due to the grating effect. Therefore, the reflected and diffracted signals in substrate can be effectively coupled to the substrate surface, and the signals in the place of the detector can be enhanced by the interference effect. Therefore, except for the Eq. (1), the other two equations should be considered as:

\[
2nH = k_2 \cdot \lambda + n(1 + \sec \beta), \ (k_2 = 1, 2, 3, \cdots).
\]

And

\[
m\lambda = nP(\sin \alpha + \sin \beta), \ (m = 1, 2, 3, \cdots).
\]

where \(m\) is the diffraction order, \(n\) is the refractive index \((n = 3.45\ \text{for Si})\), \(H\) is the substrate thickness, \(P\) is the grating period, \(\alpha\) and \(\beta\) are the incident angle and diffraction angle respectively. For a plane wave, when \(\alpha = 0\), Eq. (3) can be rewritten as

\[
m\lambda = nP \sin \beta, \ (m = 1, 2, 3, \cdots).
\]

The zero order diffraction corresponds to \(m = 0\) in the Eq. (4). At this time, the diffraction angle is independent of the wavelength and the signal cannot be diffracted by the grating. When \(m\neq0\), the diffraction angle varies with the wavelength.

**Fabrication process.** The reflective grating-coupled structure and the F-P resonator were respectively applied in the preparation of the Nb\(_5\)N\(_6\) detector chip. Firstly, 110 nm-thick Nb\(_5\)N\(_6\) film and 220 nm-thick Au electrodes were deposited on Si substrates with different thickness by using radio frequency (RF) magnetron sputtering. Then, the fabrication of Nb\(_5\)N\(_6\) microbridge was finished after the steps of photolithography and
reactive ion etching (RIE). The size of the single Nb$_5$N$_6$ detector was 210$\mu$m $\times$ 185$\mu$m, and the period of the array detectors was 320$\mu$m as shown in Fig. 3(b). Secondly, the fabrication of the F-P resonator and the reflective grating-coupled structure on the back of Si substrates. A 220 nm gold layer was deposited on the back of substrate to form the F-P resonator. The reflective grating-coupled structure was formed on the back of the substrate through the photolithography and the inductively coupled plasma (ICP) technology. In ICP process, RF and ICP power were 30 W and 1000 W respectively. The 15 minutes ICP etching took place in a gas mixture of SF$_6$ (50 sccm) and C$_2$F$_6$ (50 sccm) at a total pressure of 20 mTorr. The groove depth about 15$\mu$m was formed. Finally, a 220 nm gold layer was deposited on the top. The fabricated grating-coupled structure is shown in Fig. 3(a).

**Measurement setup.** A quasi-optical test system constructed using two off-axis parabolic mirrors is shown in Fig. 7. The incident signal from a signal source, whose frequency can be tuned from 0.26 THz to 0.365 THz, was modulated using a 1 KHz TTL signal. The input power was measured by a thermal power sensor (OPHIR, 3 A-P-THz) at Nb$_5$N$_6$ array detector place. The voltage responses of the Nb$_5$N$_6$ detector which was biased at 0.4 mA were read out by a lock-in amplifier.$^{11}$

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**Author Contributions**
L.K. and X.Q.J. proposed and supervised the grating-coupled structure and device design to improve detection efficiency of the THz detector. P.X., X.C.T. and C.T.J. completed numerical simulations. P.X., X.C.T., C.T.J., S.M.Z., J.Z. and D.F.P. have performed experiments and characterizations. P.X., X.C.T., X.Q.J., J.C., L.K. and P.H.W. discussed the simulations and analyzed the results. All authors reviewed the manuscript.

**Additional Information**
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