Terahertz Photoconductive Antennas

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Abstract: The presentation is to introduce a photoconductive (PC) antenna, how it works, what the main parameters and challenges are, how to design a PC antenna and improve its performance, and also to report the latest development. It will show that the major challenge is about how to increase the THz power and the laser (optical) to THz conversion efficiency. Some detailed examples are given to explain how a THz PC antenna could be designed and developed and some latest designs are presented.

Keywords: THz antennas, photoconductive antennas, THz radiated power, Optical-to-THz conversion efficiency, THz detection, THz emission, THz photomixer.

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Dr Huang has published over 300 refereed papers in leading international journals and conference proceedings, and is the principal author of Antennas: from Theory to Practice (John Wiley, 2008). He has received many research grants from research councils, government agencies, charity, EU and industry, acted as a consultant to various companies, and served on a number of national and international technical committees (such as the UK KTN, IET, EPSRC, and European ACE) and been an Editor, Associate Editor or Guest Editor of four of international journals. He has been a keynote/invited speaker and organiser of many conferences and workshops (e.g. IEEE iWAT, WiCom and Oxford International Engineering Programmes). He is at present the Editor-in-Chief of Wireless Engineering and Technology (ISSN 2152-2294/2152-2308), Leader of Focus Area D of European COST-IC0603 (Antennas and Sensors), Executive Committee Member of the IET Electromagnetics PN, UK national representative to the Management Committee of European COST Action IC1102 (VISTA), a Senior Member of IEEE and a Fellow of IET. 
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Preface

This PPT document was specially prepared for FERMAT. Unlike a conventional PPT file for a conference or seminar, this one has more words and no animation since you are not really listening to a presentation but reading it through quietly. I hope that we have managed to collect the right amount of information and presented in a brief and logical way so you will be able to understand it in a relaxed and enjoyable manner.

Prof Yi Huang

Liverpool, UK
Abstract

- The presentation is to introduce a photoconductive (PC) antenna, how it works, what the main parameters and challenges are, how to design a PC antenna and improve its performance, and also to report the latest development.

- It will show that the major challenge is about how to increase the THz power and the laser (optical) to THz conversion efficiency.

- Some detailed examples are given to explain how a THz PC antenna could be designed and developed and some latest designs are presented.
Keywords

THz antennas, photoconductive antennas, THz radiated power, Optical-to-THz conversion efficiency, THz detection, THz emission, THz photomixer.
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1. Introduction to THz photoconductive antennas
   1. Why THz photoconductive (PC) antenna?
   2. What is a PC antenna?
   3. How does it work?
   4. Any problems?

2. The study of photoconductive antennas
   1. The optical to THz wave conversion efficiency
   2. How to achieve high power and efficiency?
   3. Examples
   4. Some latest developments

3. Conclusions
1. Introduction to THz Photoconductive Antennas

Let’s understand THz first:

1 THz ~ 300 μm ~ 1 ps ~ 4 meV

□ Characteristics:
  - Non-ionising
  - Better resolution compared to Microwave
  - Better penetration depth compared to Infrared

□ Applications:
  - Medical imaging and Pharmaceutical industry
  - Security screening
  - Spectroscopy
  - Communications
A major problem is the THz power generation

- Typically there are two ways to generate THz signals:
  - from RF/MW devices (vacuum and solid devices) and
  - from laser and photonic devices.

- From Fig. 1 below we can see that compact THz sources exhibit low powers.
  - In nearly every case, as the frequency rises into the terahertz range, the source’s output power plummets.
  - The $Pf^2 = \text{constant line}$ is the power-frequency slope you would expect to see in a more mature RF device, while the $P\lambda = \text{constant line}$ is the expected slope for some commercial lasers.

- Why low power? The main cause is the low energy conversion efficiency (less than 1%) - we will discuss this further later.
Fig. 1 Average power vs. Frequency in THz

Why THz photoconductive (PC) antennas?

They are popular for the following main reasons:

- They can operate in **room temperature** without cryogenic cooling unlike quantum cascade lasers;
- They are **small in size** unlike backward wave oscillators;
- They can operate at **higher THz frequencies** unlike THz vacuum and solid state devices;
- They do **not require high power laser sources** unlike nonlinear crystals;
- They can produce **short pulses with high peak powers** although the average powers are low;
- They are **tunable and economical** overall.
What is a THz PC antenna?

- A typical THz PC Antenna is given below, and has **3 elements** which is more complicated than an RF/MW antenna.

- The main feature is that the THz wave can only be generated via a laser source illuminated on the antenna gap.
How does it work?

- When a laser beam (which has the energy larger than the bandgap energy of PC material) is illuminated on the PC gap (or feeding spot) of the PC antenna, electrons and holes are generated in the PC substrate;
- Due to the bias voltage, photo-induced currents are formed by these electrons and holes;
- This time varying currents radiate THz waves.
There are two types: pulsed and CW

- **A pulsed system:** broadband and one pulse laser required
  - Ultra-short laser pulse (< 100 fs)
  - $\lambda_{opt} \sim 800\,\text{nm} \text{ or } 1550\,\text{nm}$

- **A CW system:** narrow band and two lasers at different frequencies
  - Continuous wave (CW) lasers at $\omega_2$ and $\omega_1$
  - Radiated THz wave, typically $30\,\mu\text{m} < \lambda_{\text{THz}} < 3\,\text{mm}$

Side view of a PC antenna

THz pulsed wave

THz CW wave with the frequency of $\omega_2 - \omega_1$
A typical THz time-domain spectroscopy system.
Some early PC antennas

The study of PC antennas started in 1980s. The design of the antenna was based on try and error, there was no theory to guide the design.

Auston 1984 [2]

Smith 1988 [3]
Since the THz power generated was very small and the bandwidth was narrow, thus different electrodes/antennas were developed. Some examples are given below, but these PC antennas are different from the conventional RF/MW antennas and do not work in the same way. A summary of the comparison between them is presented in the next slide.

To increase impedance [4]

To broaden the BW [5]
## Comparison of THz PC antennas and RF/MW antennas

<table>
<thead>
<tr>
<th>Parameter</th>
<th>THz PC antennas</th>
<th>RF/MW antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation source/feeding</td>
<td>Laser pulses</td>
<td>Transmission line</td>
</tr>
<tr>
<td>Substrate material</td>
<td>High resistive semicond. PC material</td>
<td>Low loss dielectric materials</td>
</tr>
<tr>
<td>Antenna electrode material</td>
<td>AuGe and Ti/Au on LT GaAs substrate</td>
<td>Highly conductive metals like copper</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>biased</td>
<td>no*</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Complex and expensive</td>
<td>Relatively easy and cheap</td>
</tr>
<tr>
<td>Computer aided design</td>
<td>Not available in one package</td>
<td>Available</td>
</tr>
</tbody>
</table>

* Some RF/MW antennas like the ones based upon RF-MEMS switches and p–i–n diodes require biasing.

**Two problems have been identified below:**
Problem 1 – low power

THz antennas in a pulsed system

From all these examples we can see the output power of THz PC antennas is still very low. This is the bottleneck for wide uptake of THz technology.
Problem 2 – low efficiency

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Pump Power (mW)</th>
<th>Output Power (μW)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole (length 30 μm, width 20 μm)[6]</td>
<td>15</td>
<td>0.34</td>
<td>2.2 x10^{-3}</td>
</tr>
<tr>
<td>Dipole (length 20 μm, width 10 μm)[6]</td>
<td>15</td>
<td>0.12</td>
<td>8 x10^{-4}</td>
</tr>
<tr>
<td>Dipole (length 10 μm, width 20 μm)[6]</td>
<td>15</td>
<td>0.07</td>
<td>4.6 x10^{-4}</td>
</tr>
<tr>
<td>Bowtie (bow angle 90 deg)[6]</td>
<td>15</td>
<td>2</td>
<td>0.013</td>
</tr>
<tr>
<td>Bowtie antenna (@ 0.5 THz)[13]</td>
<td>10</td>
<td>0.005</td>
<td>5x10^{-5}</td>
</tr>
</tbody>
</table>

Why the THz antenna is so inefficient?
2. The Study of THz PC Antennas

- There have been a lot of studies into THz PC antennas since 1980s, so far the IEEE Xplore digital lib has over 450 papers in “photoconductive antennas” and over 2000 papers in “THz antennas”.
- Over half of them were published over the past 5 years (2010 to 2015)!
- Nona-fabrication has made it possible to realise a wide range of THz antennas.
- People have studied the subject from almost every aspect you many think of, and some progress has been made; but this is still a subject in its infancy.
2.1 The optical to THz conversion efficiency

Let’s focus on the main problem: optical to THz wave conversion efficiency. The entire process from optical (laser) power to THz wave generation can be divided into three parts:

1. Generation of THz photocurrent from the optical power in the PC material. The related efficiency; *i.e.* **optical-to-electrical efficiency**, $\eta_{LE}$, can be defined as the ratio of the generated THz power in the PC gap to the optical power;

2. The amount of coupled THz power from the PC gap to the antenna electrodes; *i.e.* **matching efficiency**, $\eta_m$

3. The amount of coupled THz wave from the antenna to the free space; *i.e.* **radiation efficiency**, $\eta_r$. 
The three efficiencies can be calculated:

<table>
<thead>
<tr>
<th>Efficiency Type</th>
<th>THz Pulsed antenna [21]</th>
<th>THz CW photomixer antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>optical-to-electrical efficiency, $\eta_{LE}$ [22]</td>
<td>$\frac{R_{\text{app}} I_{\text{avp}}^2}{P_{\text{av}}} = \frac{\eta_L h f l^2 e^2 \mu_e \tau_c^2 V_{\text{bias}}^2 P_{\text{av}}^2}{e\mu_e P_{\text{av}} t_{\text{rep}} P_{\text{av}} h^2 f^2 l^4}$</td>
<td>$\frac{R_{cw} I_{avc}^2}{P_{av}} = \frac{R_{cw} \eta_q e P_{av}}{P_{av}} \frac{1}{h f (1 + \omega^2 \tau_c^2)^{1/2}}$</td>
</tr>
<tr>
<td>matching efficiency, $\eta_m$</td>
<td>$1 - \left</td>
<td>\frac{Z_{\text{free}} / \sqrt{\varepsilon_r} - R_{\text{app}}}{Z_{\text{free}} / \sqrt{\varepsilon_r} + R_{\text{app}}} \right</td>
</tr>
<tr>
<td>radiation efficiency, $\eta_r$</td>
<td>Requires analytical/numerical simulation</td>
<td>Requires analytical/numerical simulation</td>
</tr>
</tbody>
</table>
because laser induced photo current at the gap:

\[ I = \frac{eV_b \mu_e \tau \eta_L P_L}{hf_L l^2} \]

- \( P_L \) is the power of input laser
- \( l \) is the gap length
- \( V_b \) is the applied bias voltage
- \( \mu_e \) is the free carrier mobility of the PC material.
- \( \tau \) is the photocurrent decay time
- \( e \) is the electron charge \((= 1.6602 \times 10^{-19} \text{ Col})\)
- \( h \) is Planck’s constant \((= 6.626 \times 10^{-34} \text{ J} \cdot \text{s})\)
- \( \eta_L \) is the illumination efficiency
The resistance at the gap:

\[ R \approx \frac{h c f_R l^2}{\eta_L e \mu_e P_L \lambda_L} \]

- \( c \) is the speed of light
- \( \lambda_L \) is the laser wavelength
- \( f_R \) laser repetition frequency

This resistance is a function of many variables, such as the gap length, laser frequency, power, repetition frequency and parameters of PC material like carrier mobility and illumination efficiency.
The induced electrical power at the gap:

\[ P_E = I^2 R \approx \left( \frac{eV_b \mu_e \tau \eta_L P_L}{h \nu_L l^2} \right)^2 \frac{h \nu_f R l^2}{\eta_L e \mu_e P_L \lambda_L} \]

\[ = \frac{eV_b^2 \mu_e \tau^2 \eta_L P_L c \nu_f}{h \nu_L l^2 \lambda_L} = \frac{eV_b^2 \mu_e \tau^2 \eta_L P_L f_R}{h \nu_L l^2} \]

**Laser-to-electrical power conversion efficiency:**

\[ \eta_{LE} = \frac{P_E}{P_L} \approx \frac{eV_b^2 \mu_e \tau^2 \eta_L f_R}{h \nu_L l^2} \]
The total efficiency for PC antenna:

\[ \eta_T = \eta_{LE} \cdot \eta_m \cdot \eta_r = \frac{eV_b^2 \mu_e \tau^2 \eta_L f_R}{hf_L l^2} \cdot \left[ 1 - \left( \frac{Z_a - R}{Z_a + R} \right)^2 \right] \cdot \eta_r \]

This interesting result means that the efficiency is proportional to:

- bias voltage square \((V_b^2)\),
- photoconductive material properties \((\mu_e \tau^2)\),
- laser repetition frequency \((f_R)\), and illumination efficiency \((\eta_L)\),

but inversely proportional to:

- laser frequency \((f_L)\) and
- the gap length square \((l^2)\).
Material selections

- Some important material parameters are shown earlier on slides 20 and 23: the carrier mobility and photocurrent decay time. Other parameters such as resistivity and breakdown voltage are also important. The overall best material so far seems to be LT-GaAs:

<table>
<thead>
<tr>
<th>Material</th>
<th>Carrier lifetime (ps)</th>
<th>Mobility (cm²·V⁻¹·s⁻¹)</th>
<th>Resistivity (Ω·cm)</th>
<th>Breakdown field (V·cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT-InGaAs</td>
<td>Larger than LT-GaAs [27]</td>
<td>26 [28]</td>
<td>760 [28]</td>
<td>~6 × 10⁴ [28]</td>
</tr>
</tbody>
</table>
An example

Let’s assume we have a PC antenna with $f_R = 80 \text{ MHz}$, $P_L = 36 \text{ mW}$, $\lambda_L = 800 \text{ nm}$ (about $375 \text{ THz}$ in frequency and $1.55 \text{ eV}$ in photon energy), $l = 4 \mu\text{m}$, and $\eta_L = 2/3$, $\mu_e = 1000 \text{ cm}^2/\text{Vs}$ and $\tau = 0.5 \text{ ps}$ for LT-GaAs.

The resistance of the PC gap, $R = 0.827 \Omega$

If the bias voltage is assumed to be $60 \text{ V}$ laser-to-electrical power conversion efficiency $\eta_{LE} = 1.936 \times 10^{-4}$ – this is very small.

If the antenna is a half-wave dipole on LT-GaAs substrate with impedance $Z_a = 27 \Omega$, the matching efficiency is $\eta_m = 0.1153$.

If $\eta_r = 80\%$, the total antenna efficiency is $1.784 \times 10^{-5}$, which is very small indeed.
Now we see clearly why the efficiency is very low: **not just because of the impedance matching, but more importantly the material, laser and bias voltage!**

The analysis here has used approximations such as
- The gap area is uniformly illuminated by laser
- The field in the gap area is uniform

Other things to be taken into account including e.g.
- Saturation
- Breakdown voltage at the gap

For CW THz system, the impedance mismatch is worse (\( R \) is about 10k \( \Omega \)) than pulsed THz system.
The new PC antenna efficiency formula obtained clearly shows what and how the parameters and variables linked to the efficiency.

For a PC antenna, the total efficiency is the product of laser-to-electrical, impedance matching and radiation efficiencies.
2.2 How to achieve high power and efficiency?

Aim: High THz power and/or High optical-to-THz conversion efficiency

Main contributors:

- High time-varying transient photocurrent
- Good antenna impedance matching
- Good coupling of THz wave to air

PC material and the gap (named as photomixer part)

Design of the gap and electrodes
Aim: High THz power and/or high optical-to-THz conversion efficiency

Main contributors:
- High time-varying transient photocurrent
- Good antenna impedance matching
- Good coupling of THz wave to air

High photo-carrier density
- High optical power
- Delaying screening effect
- Laser excitation spot shape e.g. elliptical

High photo-carrier acceleration
- Short laser pulse duration
- Good heat sinking
- Gap size of the antenna e.g. larger antenna gap

Large bias voltage
- Uniform E-field distribution in the antenna gap
- Large breakdown voltage of substrate material
- Antenna gap geometry e.g. antenna with sharp tip ends
- Large dark resistivity of the antenna
Typical design requirements

- **Photomixer part**
  - Small capacitance
  - Uniform E-field
  - Strong E-field

- **Antenna part**
  - Large antenna resistance;
  - Source resistance of THz photomixer antennas are very large
  - Directional pattern

These are just typical requirements to ensure a good energy conversion efficiency as we have seen from total efficiency formula.
2.3 Examples: 4 photomixer antennas

(1) Bare gap

(2) Interdigitated

(3) Rectangular tip-to-tip

(4) Nano-trapezoidal tip-to-tip – new design
Capacitance value comparison

<table>
<thead>
<tr>
<th>Photomixer</th>
<th>Capacitance (fF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare gap</td>
<td>1.26</td>
</tr>
<tr>
<td>Interdigitated fingers</td>
<td>2.63</td>
</tr>
<tr>
<td>Rectangular tip-to-tip</td>
<td>2.4</td>
</tr>
<tr>
<td>Nano-trapezoidal tip-to-tip</td>
<td>2.28</td>
</tr>
</tbody>
</table>

The new design has met the design requirement: small capacitance
Amplitude of E-field in the near field of the 4 antennas.
E-field on the electrode plane

The new design has also met **Strong E-field** requirement

More than 2 times
Antenna source resistance

Source resistance = 483 kΩ

Source resistance = 196 kΩ

It is still very large and an antenna with improved resistance is required.
The new THz antenna with an improved matching

(1) Nano-trapezoidal tip-to-tip Photomixer

(2) Antenna for improving the impedance matching
Antenna resistance improves from about 400 Ω to 2.6 k Ω. Therefore, matching efficiency enhances from 0.03% to 5%.

Design requirement: Large antenna resistance
To improve the radiation pattern

Alternatively, Si hemispherical lens could be used, the drawback is that the positioning of the lens could be tricky, also the gain improvement is limited
The antenna radiation pattern

**yoz plane**

\[ E_\theta \text{ at } \phi = 90^\circ \]

**xoz plane**

\[ E_\theta \text{ at } \phi = 0^\circ \]
## Summary of the design

<table>
<thead>
<tr>
<th></th>
<th>Full wavelength dipole</th>
<th>New antenna without horn and without ITO layer</th>
<th>New antenna with horn and with ITO layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna resistance</td>
<td>400 Ω</td>
<td>2.6 kΩ</td>
<td>5.57 kΩ</td>
</tr>
<tr>
<td>Matching efficiency</td>
<td>0.03%</td>
<td>5%</td>
<td>10.7 %</td>
</tr>
<tr>
<td>Directivity (dBi)</td>
<td>3.65</td>
<td>9.2</td>
<td>14.3</td>
</tr>
</tbody>
</table>

**Design requirement:** high directivity
Fabricated antennas

- Bare gap
- Rectangular tip-to-tip
- Trapezoidal tip-to-tip

Packaged antenna

- Emitter case: For biasing
- Detector case: For measuring the signal

For connecting optical fibre

Lens
Photomixer part is tested with a known bowtie antenna.

[31]
Dark current was more than 30 times smaller.

<table>
<thead>
<tr>
<th>photomixer</th>
<th>Photocurrent (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare gap</td>
<td>1.7</td>
</tr>
<tr>
<td>Rectangular tip-to-tip</td>
<td>1.9</td>
</tr>
<tr>
<td>Nano-trapezoidal tip-to-tip</td>
<td>2.2</td>
</tr>
</tbody>
</table>
THz photomixer as an emitter

We can see that the new design has produced the most power over a wide frequency band.

2 times

7 times
In this case, the measured noise level (when there is no laser illumination) is $0.8 \times 10^{-10} \text{ W/} \sqrt{\text{Hz}}$. 
Measurement results

THz photomixer as a detector

We can see again that the new design has produced the best signal to noise ratio (SNR) over a wide frequency band.
2.4 Some latest developments

Due to the significant advancement in nano-technology, various PC antenna designs have been fabricated. In the example below, 3-D electrodes were designed and made, very high efficiency (7.5%) has been achieved. This can be explained using the total efficiency theory discussed earlier to explain: the structure has much improved $\eta_{LE}$.

7.5% Optical-to-Terahertz Conversion Efficiency Offered by Photoconductive Emitters With Three-Dimensional Plasmonic Contact Electrodes

Shang-Hua Yang, Graduate Student Member, IEEE, Mohammad R. Hashemi, Member, IEEE, Christopher W. Berry, Member, IEEE, and Mona Jarrahi, Senior Member, IEEE
Configuration comparison:

Conventional 2D

New 3D
Much better O/E conversion
Results:

2D structure

3D structure

Conversion efficiency

Much improved efficiency and power were obtained when the pump power was low (1.4 mW) but the improvement is less at higher pump powers – maybe due to saturation.
Due to the complexity of the THz PC antenna, there is no single software package which is suitable for the antenna simulation, progress has been made in this area by taking the electron and hole currents and Maxwell’s equation into account (such as the paper below)

A complete solution to both the optical-to-electrical and the antenna radiation in one package is yet to be found
A new way to simulate a THz PC antenna?

- There have been some efforts on linking the optoelectronic analysis and electromagnetic (EM) simulation which is very important for optimized designs. The basic steps are:

  - **Part 1: Optoelectronic analysis**
    - With tools like TCAD Sentaurus
    - *Employing the Drude-Lorentz model*

  - **Part 2: EM analysis**
    - *With available commercial tool i.e CST*

1) THz photocurrent can be derived

2) Fed into the EM tool

3) Far field analysis
A different angle to view the PC antenna:

- Some people have considered the PC antenna from the optical point of view, a good example is given in the paper below, where the conventional RF/MW antenna impedance and matching have not been considered. The focus was on maximizing the optical to electrical conversion which is a major limiting factor on the efficiency of the PC antenna as we have shown earlier.

- How to further improve the PC antenna performance is still a question to be answered.
Conclusions

- We have introduced THz PC antennas and identified their problems: low power and low efficiency.

- An approximate formula for the total efficiency of a PC antenna has been obtained which clearly shows how the efficiency is linked to the parameters of the PC antenna.

- A new design example has been presented and analysed. The results have shown a better performance has been obtained when compared with some exist designs.

- Some of the latest developments have been presented. It has shown that significant improvements have been made but still a long way to go if we would like to achieve relatively high antenna efficiency (say > 50%).
References


References


[27] S. J. Jo and e. al, "Carrier dynamics of low-temperature-grown In_{0.53}Ga_{0.47}As on GaAs using an InGaAlAs metamorphic buffer," *Applied Physics Letter*, vol. 86, p. 111903, 2005


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