

# 太赫兹动态器件及高速直接调制技术

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# 提纲

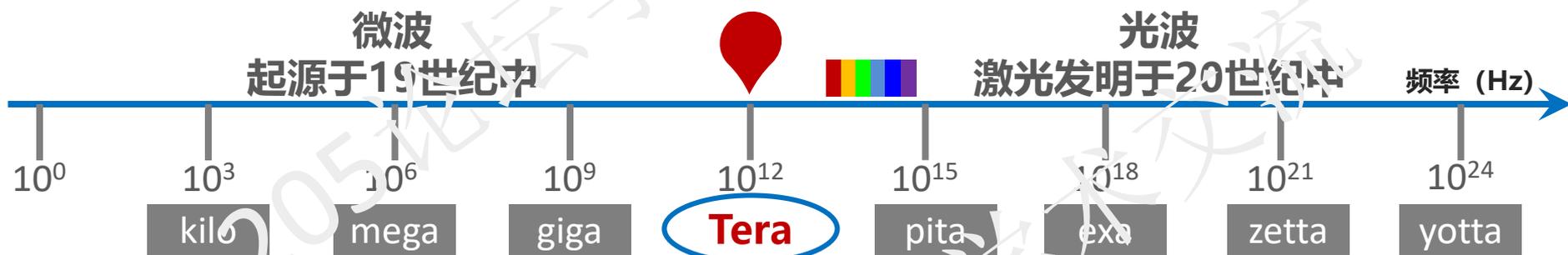
- 1 太赫兹动态调制器件研究现状
  - 2 太赫兹阵列调制器件-metasurface
  - 3 太赫兹片上调制器件-metachip
  - 4 太赫兹调制器件发展的挑战和思考
-

# 太赫兹频谱概述

## 太赫兹—电磁频谱研究的“频谱空隙”



20世纪90年代起步



- ✓ 处于微波电子学与红外光子学的交叉、过渡区域
- ✓ 频率从0.1到10THz, 频谱资源极其丰富
- ✓ 是被公认为有重要学术价值和巨大应用前景的频率窗口

# 太赫兹通信技术概述

随着业务量的增加，现有频段资源日益紧张，通信容量与业务需求矛盾不断增加，

**开发新的通信频段势在必行**



空间高速骨干网

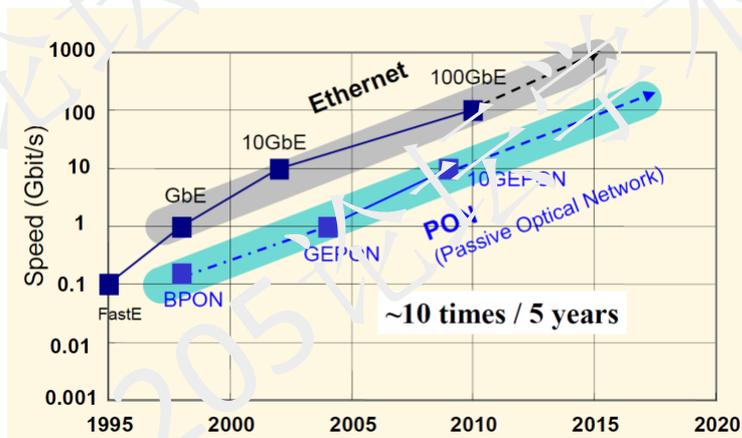
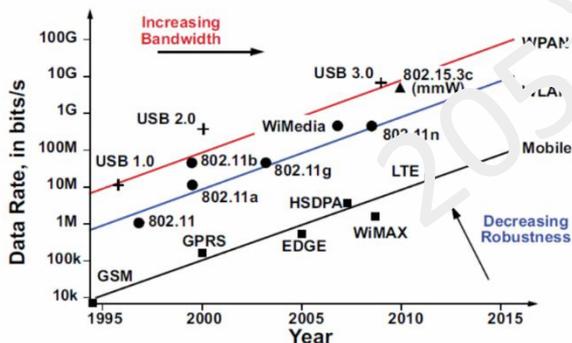


下一代移动通信



高速军事通信

Gbit/s Wireless Communication



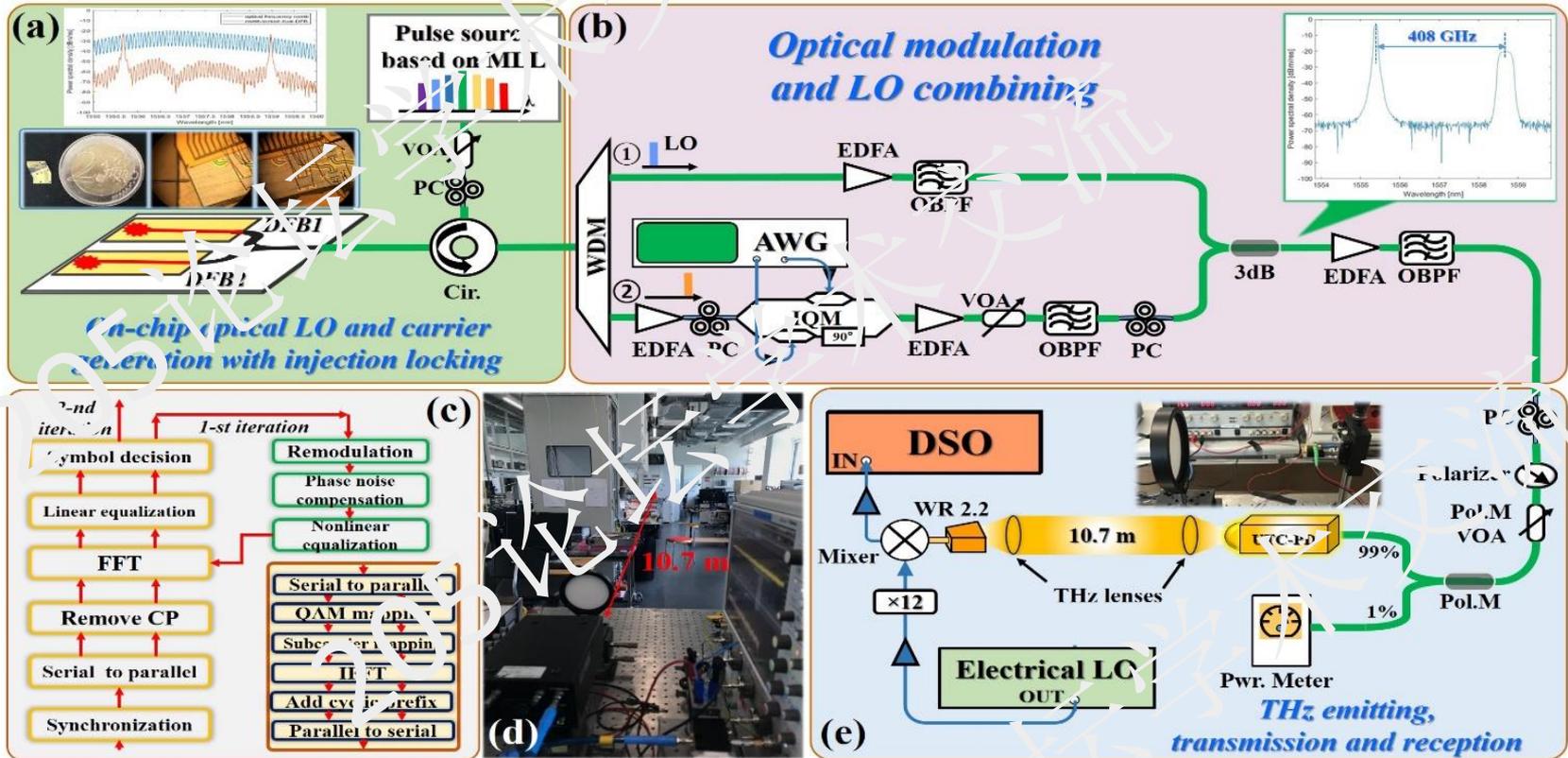
通信传输速率

按照时间以摩

尔定律增长

# 太赫兹通信架构

- 第一类太赫兹无线通信技术采用光电结合方式（微波光子学）

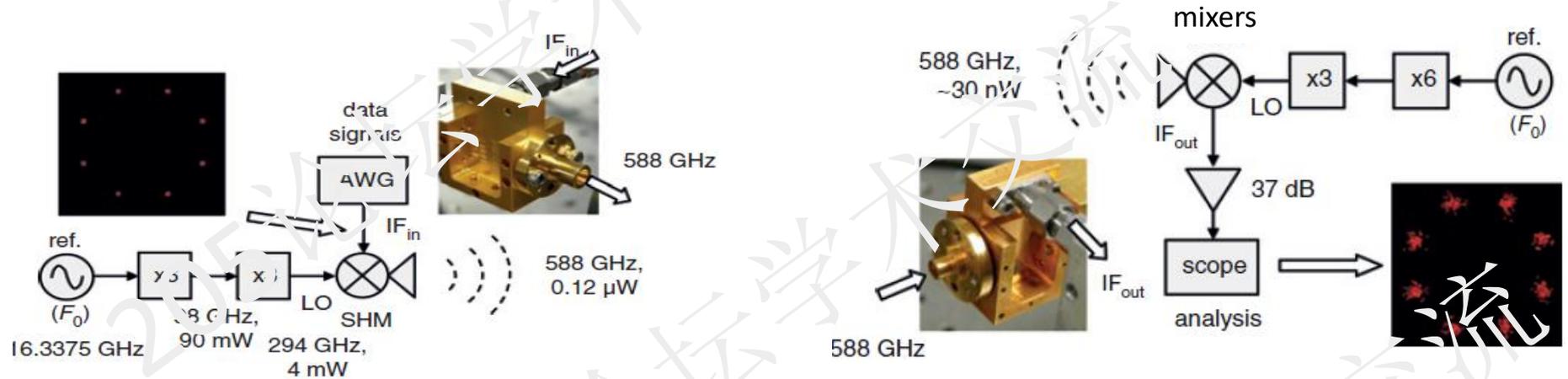


- 传输速率大于100Gbps，优点相噪低、可实现64QAM以上的调制
- 距离近、转换效率低、功耗大
- 最高速率可达到160Gbps以上

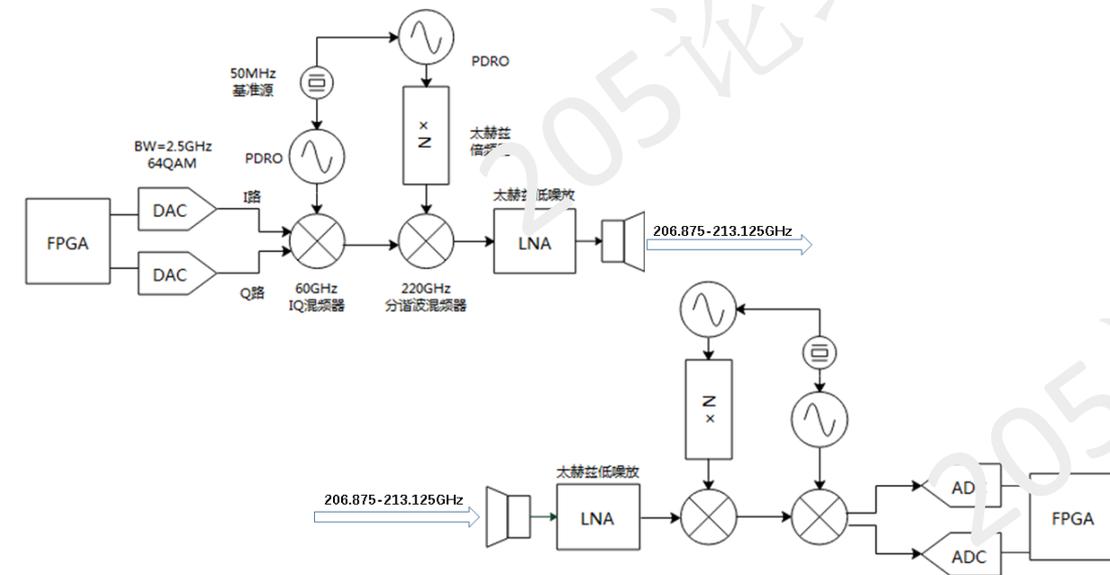
# 太赫兹通信架构

- 第二类是混频调制的全固态电子学太赫兹无线通信系统

## 沿用传统微波、毫米波上下变频技术



- 固态分离器件链路
- 0.22THz/0.34THz
- 1km、40 Gbit/s的传输速率
- 德国、美国、日本、中国
- 64QAM、仪器测试，非实时传输

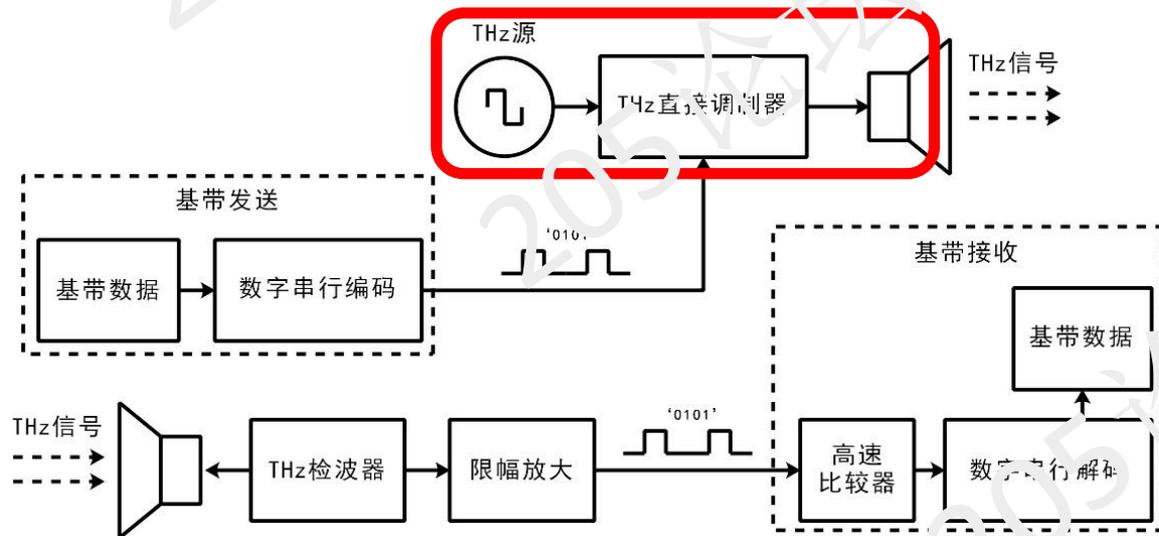


# 太赫兹通信架构

## ■ 第三类基于直接调制方式的太赫兹无线通信系统

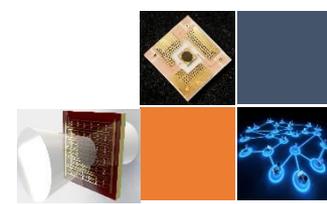


- 0.22THz、0.34THz
- 500m-1km、10 Gbit/s的传输速率
- 实时传输

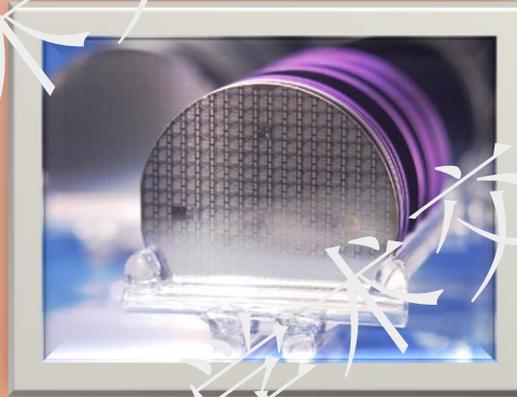


- 优势在于易集成、体积小、灵活性大，无需AD/DA
- 劣势在于缺少高速调制器
- 带宽利用率低

# 太赫兹高速调制技术



metamaterials



semiconductors



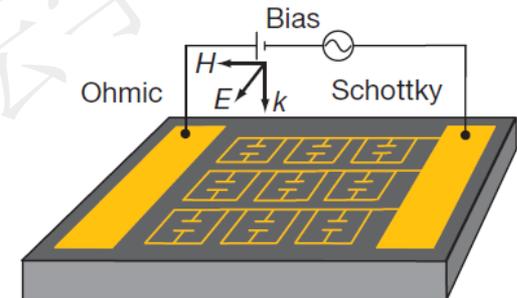
A. J. Taylor



Chen H.T.

Los Alamos

hybrid of Schottky diode and metamaterial structure



■ electrical switching of THz radiation

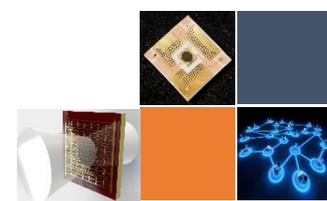
## Materials with short carrier life-time:

- Radiation damaged semiconductors (silicon)
- Low temperature grown GaAs
- ErAs/GaAs nanoisland superlattice

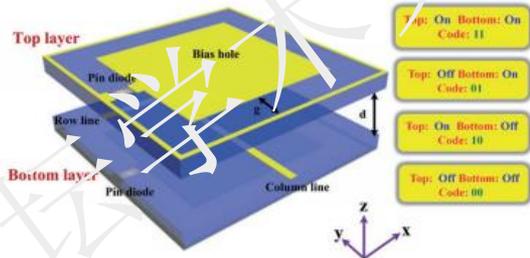
Active terahertz metamaterial devices

Nature.444, 597-600 (2006)

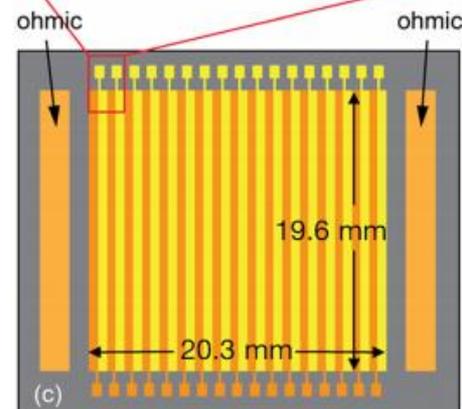
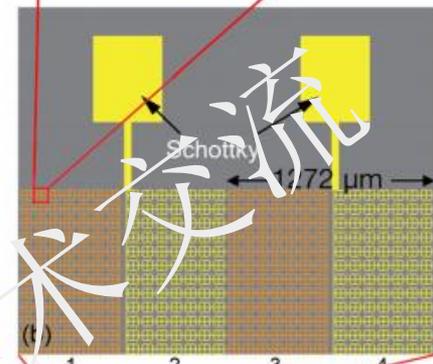
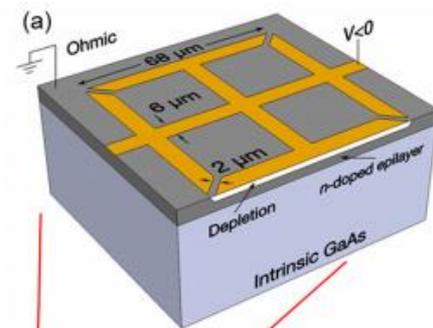
# 太赫兹高速调制技术



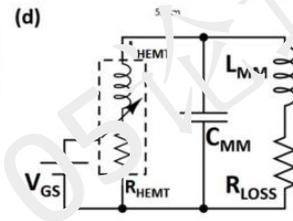
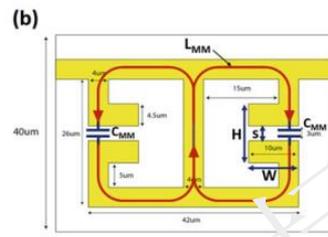
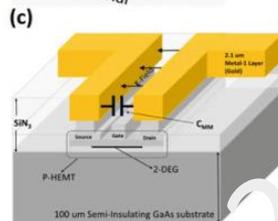
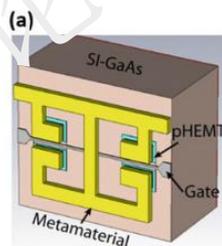
Prof. Cui Southeast University  
Information metamaterial



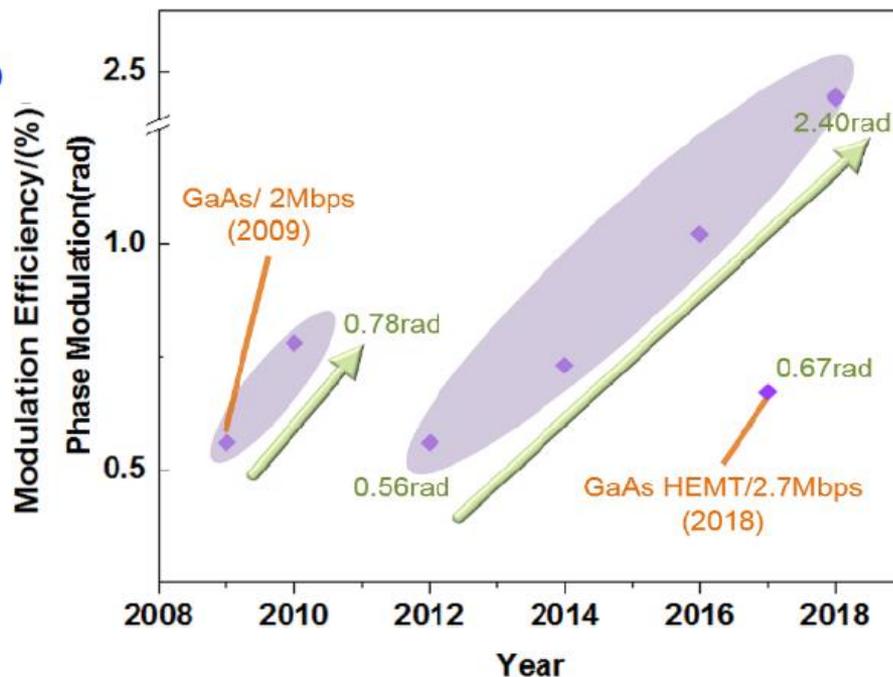
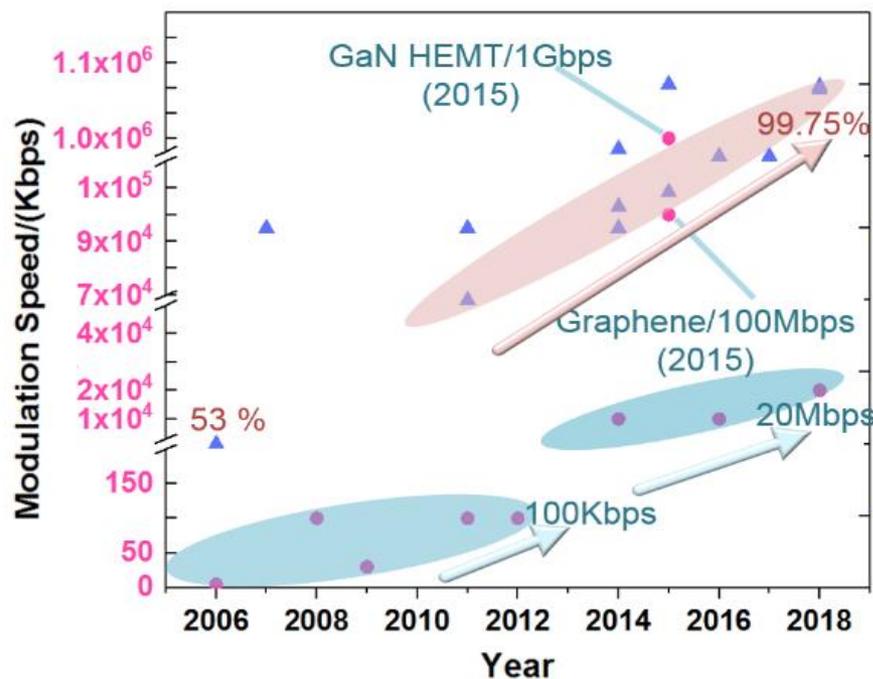
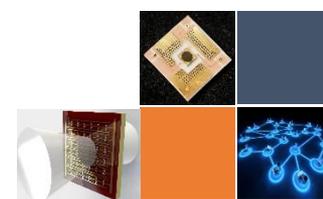
Prof. Mittleman  
Brown University



Prof. Padilla Duke University



# 太赫兹高速调制技术



Modulation depth



Close to 100%

The phase modulation



Reflection : above 300 degrees  
Transmission: over 130 degrees

Modulation rate



Break **Gbps**

# 提纲

1

太赫兹动态调制器件研究现状

2

**太赫兹阵列调制器件-metasurface**

3

太赫兹片上调制器件-metachip

4

太赫兹调制器件发展的挑战和思考

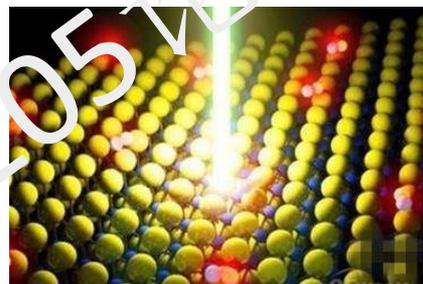
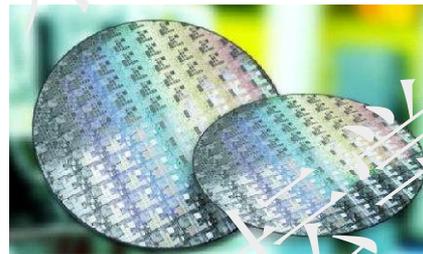
# 太赫兹阵列调制器件-metasurface

## 太赫兹外部直接调制器件发展 面临的技术难题

调制速率慢难以实现信号高速加载

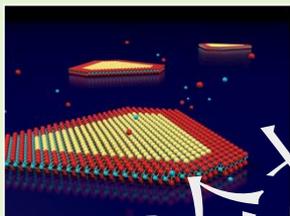
调制深度低难以实现高信噪比传输

调制损耗大难以大面积多路控制

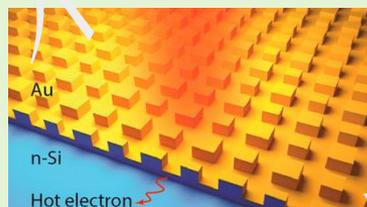


# HEMT-人工微结构阵列太赫兹调制器

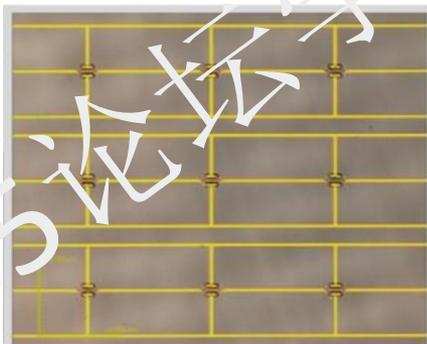
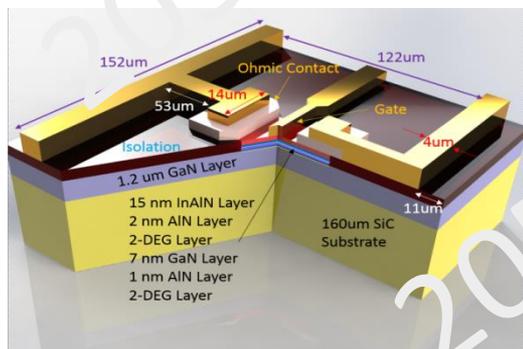
## 二维电子气



## 人工微结构



## 复合HEMT-人工微结构阵列



课题组在2009-2015年采用  
HEMT-人工微结构成功的实现了  
幅度、相位可控的太赫兹波调制  
器

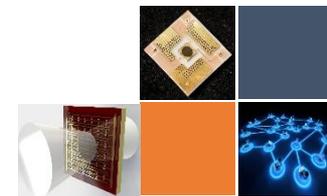
调制速率高

插入损耗小

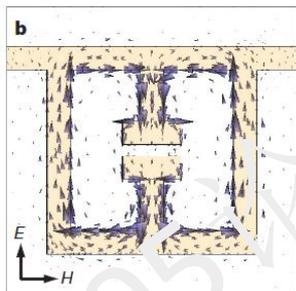
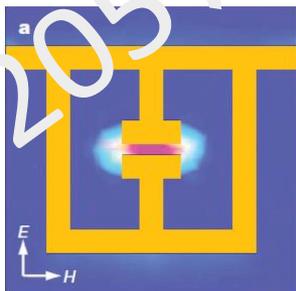
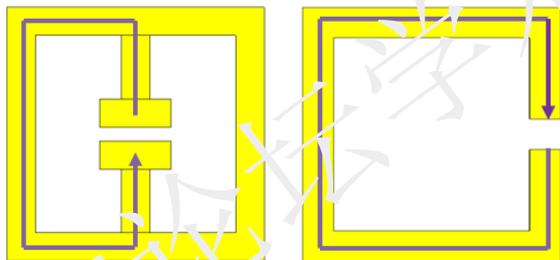
调制效率高

栅控能力强

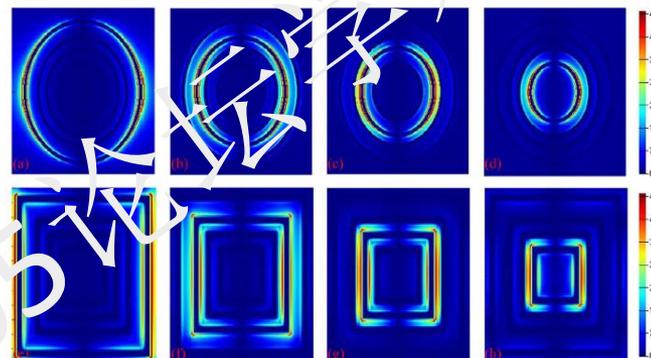
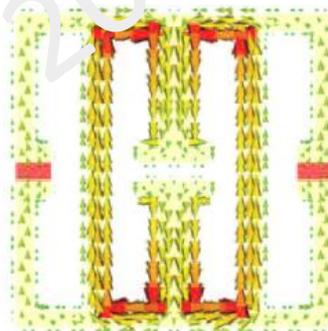
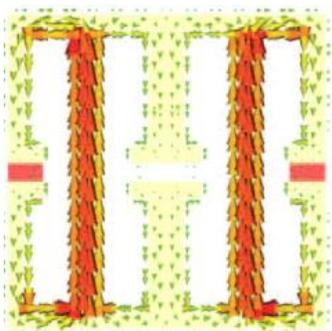
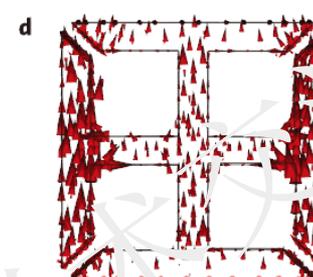
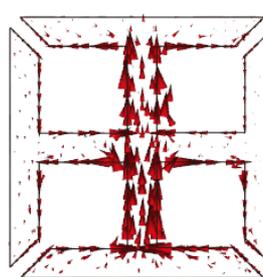
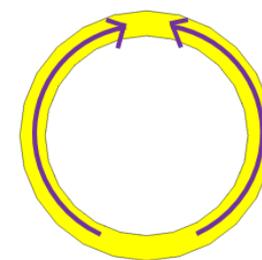
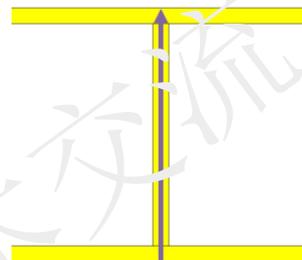
# 1. 运用meta单元间谐振实现幅度调制



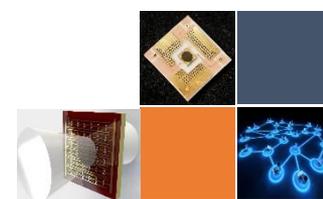
L-C resonance



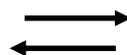
dipole oscillation



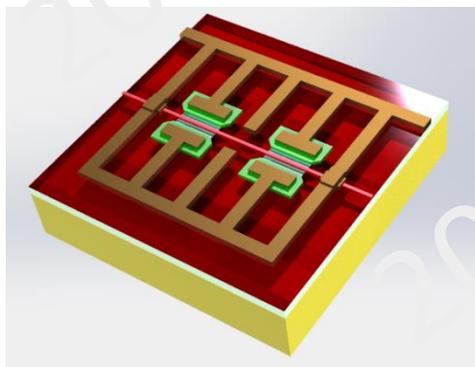
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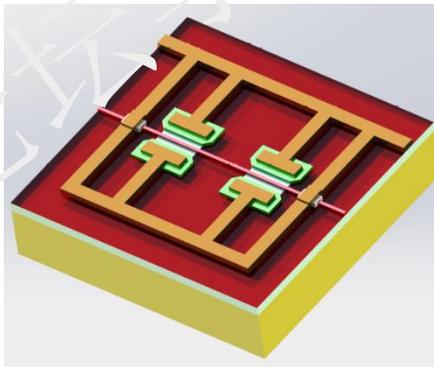
L-C resonance



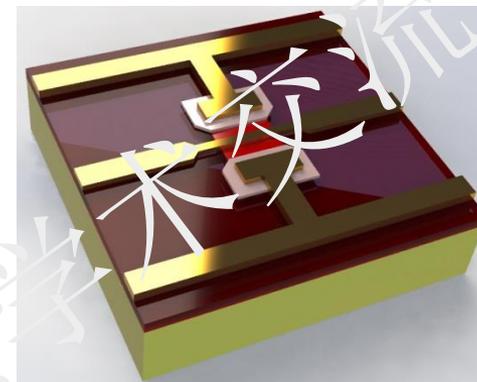
dipole oscillation



LC-LC

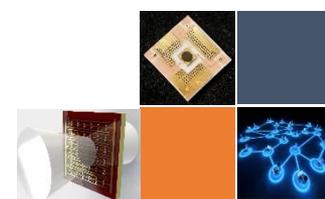


Dipole-LC

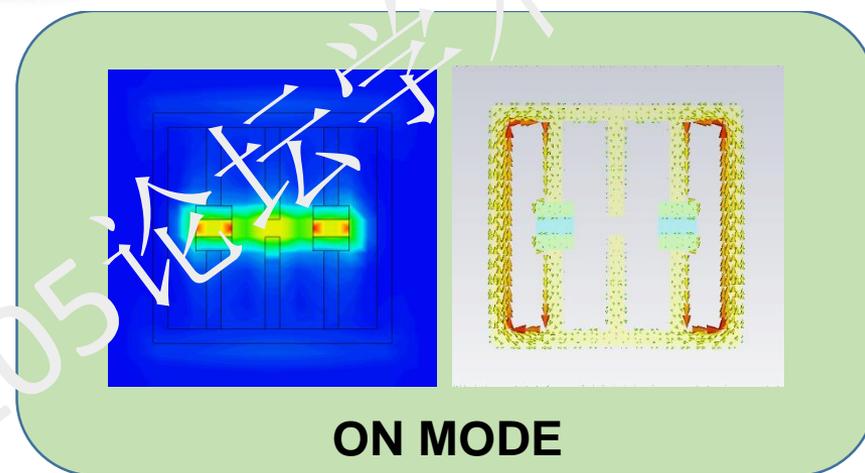
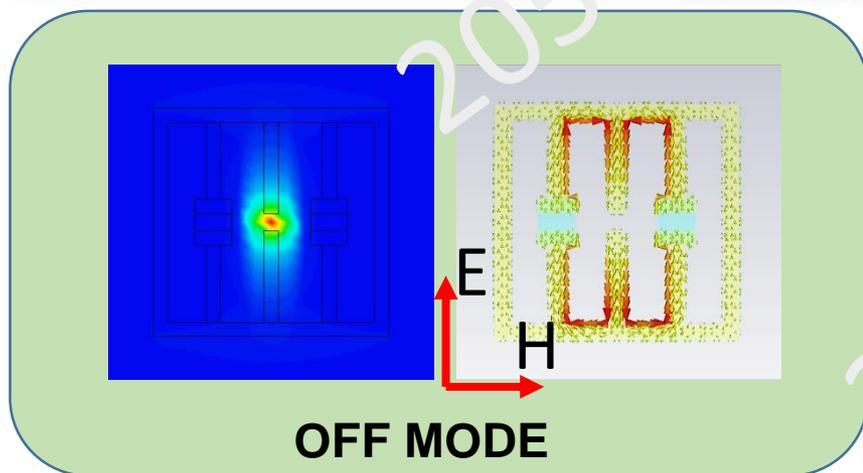
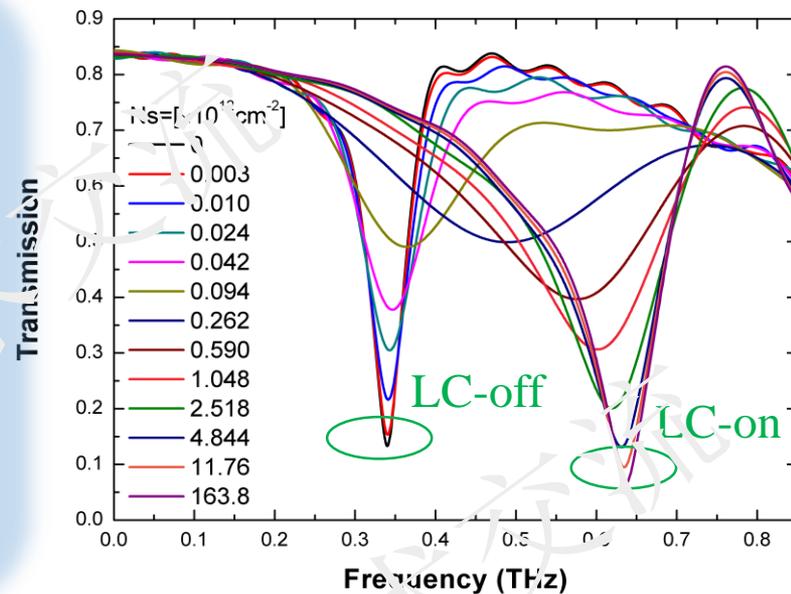
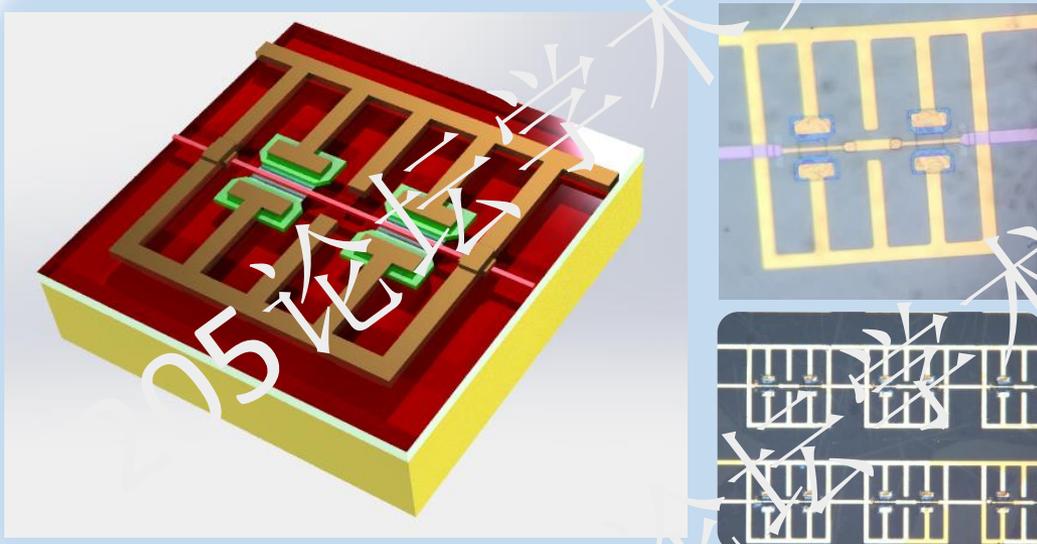


Dipole-Dipole

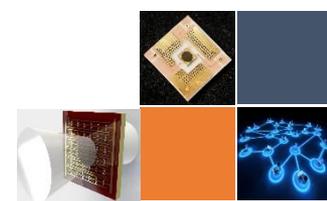
# 1. 运用meta单元间谐振实现幅度调制



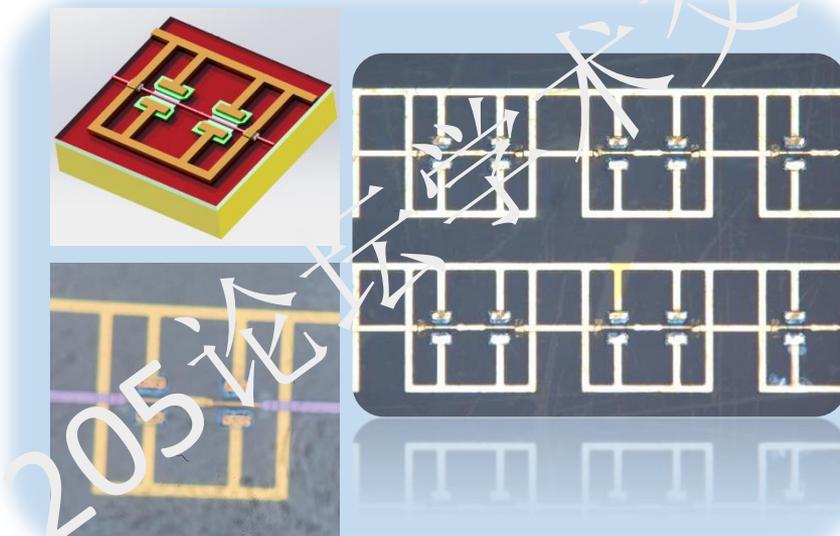
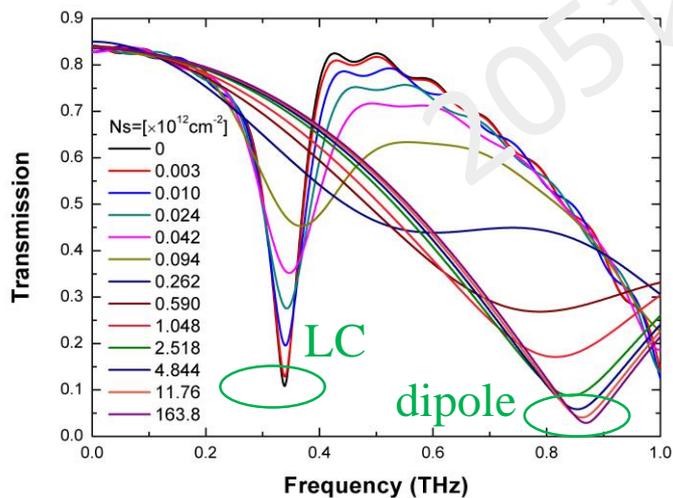
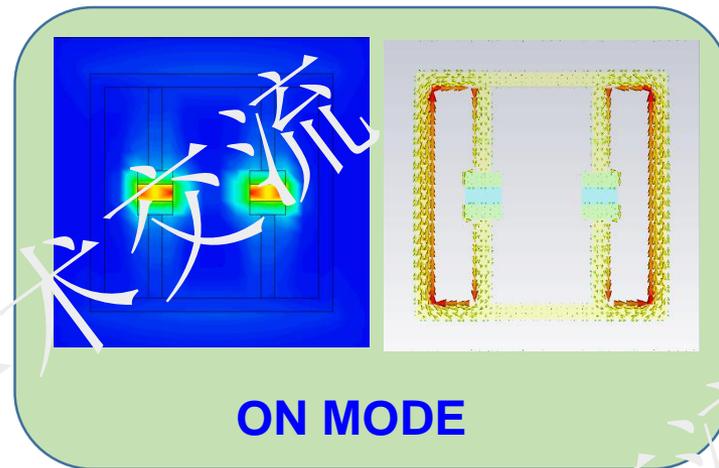
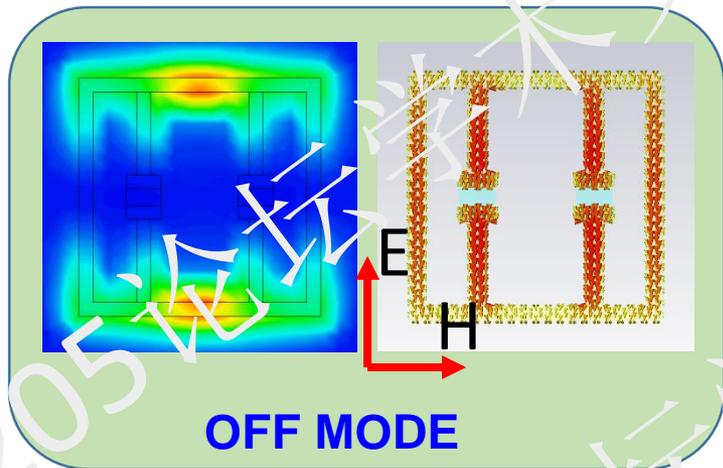
LC-LC



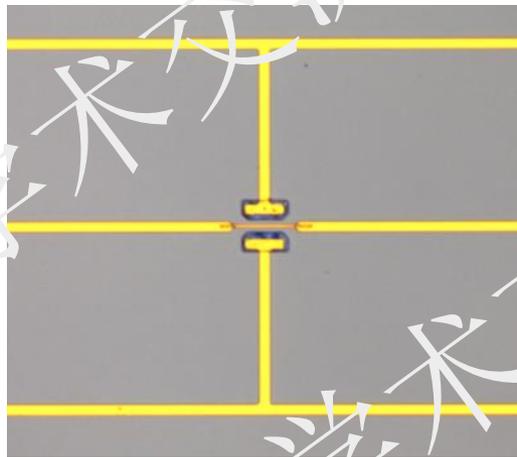
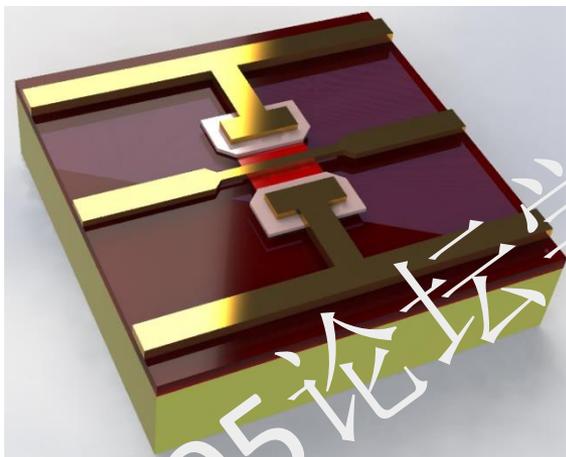
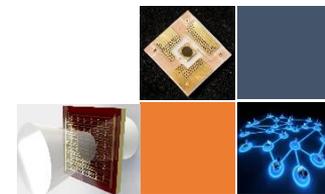
# 1. 运用meta单元间谐振实现幅度调制



## Dipole-LC



# 1. 运用meta单元间谐振实现幅度调制

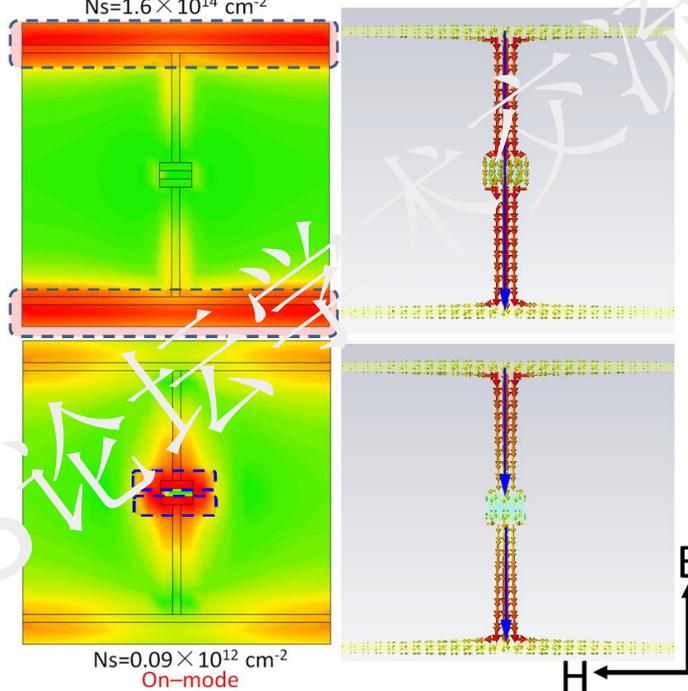
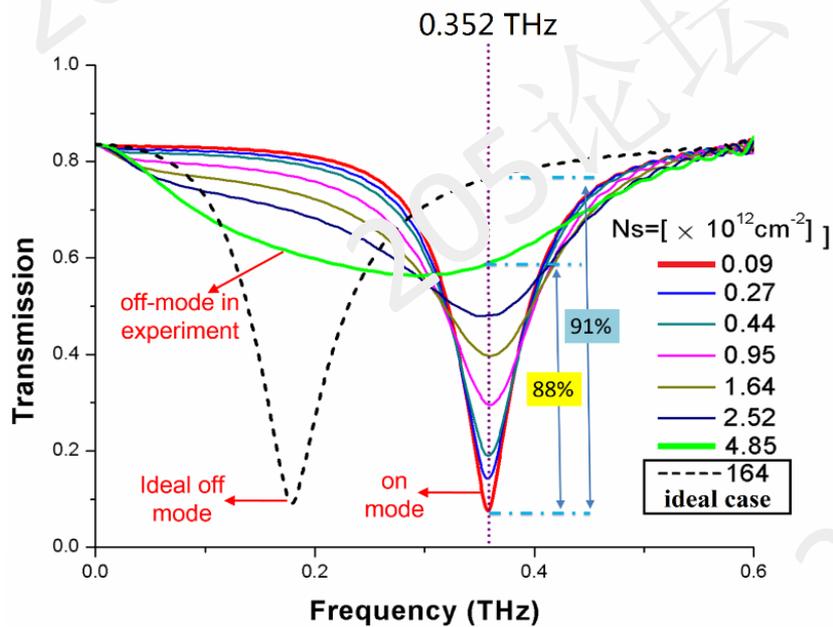


Dipole-Dipole

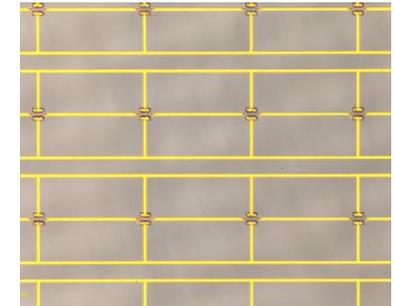
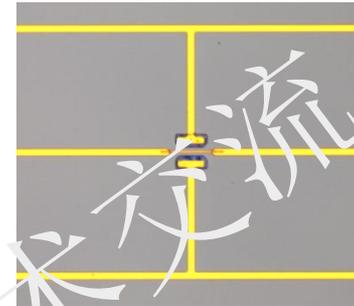
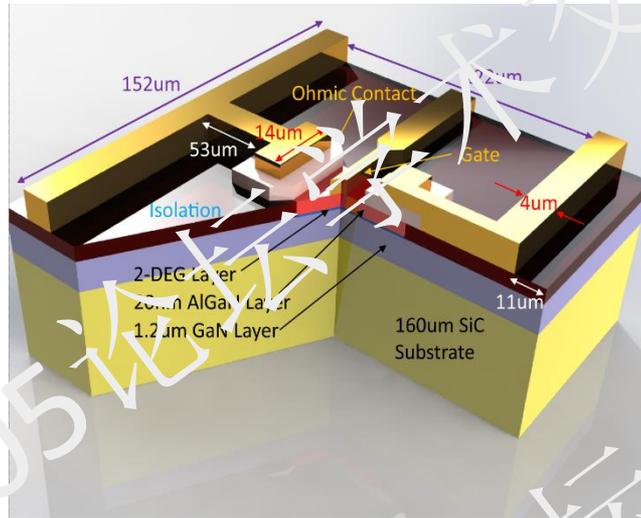
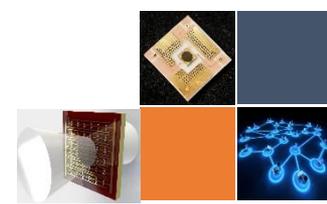
Nano Lett. 2015, 15, 3501-3506

Ideal Off-mode  
 $N_s = 1.6 \times 10^{14} \text{ cm}^{-2}$

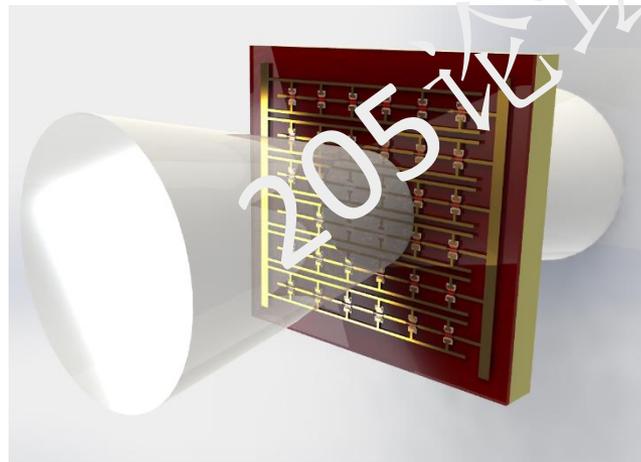
$N_s = 0.09 \times 10^{12} \text{ cm}^{-2}$   
On-mode



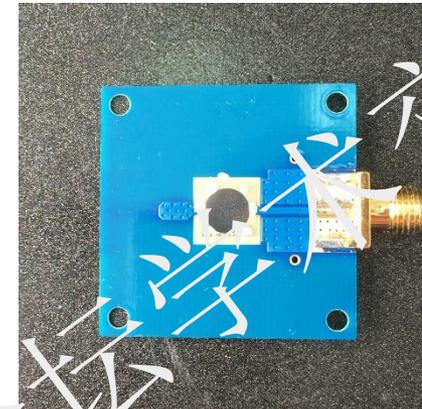
# Model and sample



Photomicrograph of the MMTM

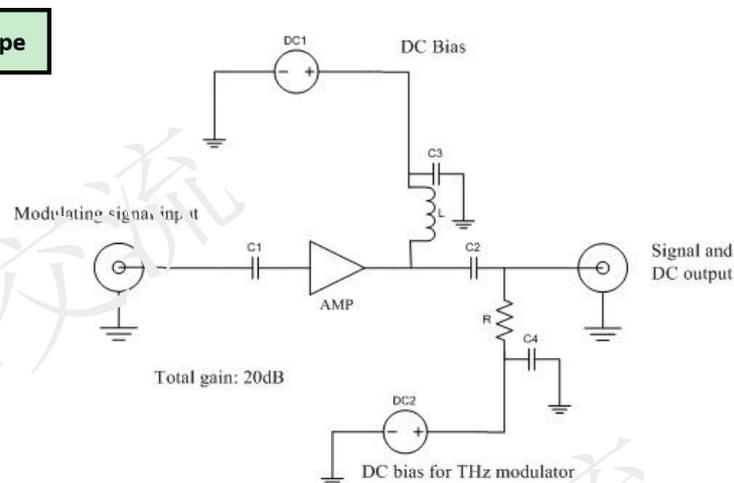
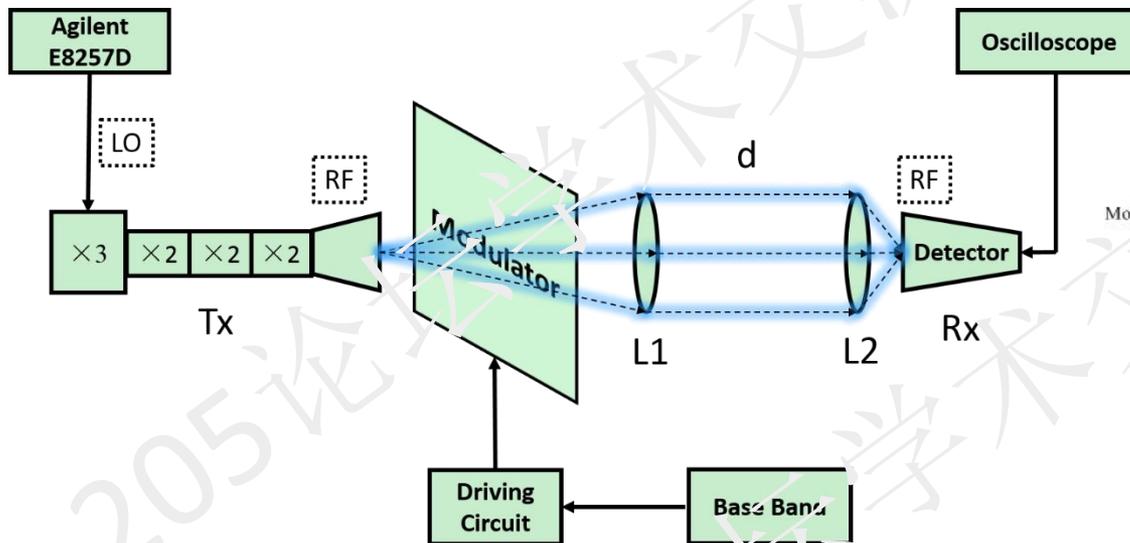
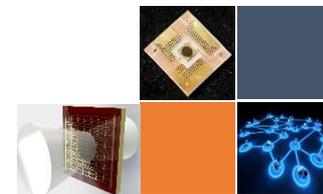


Experimental Schematic Diagram

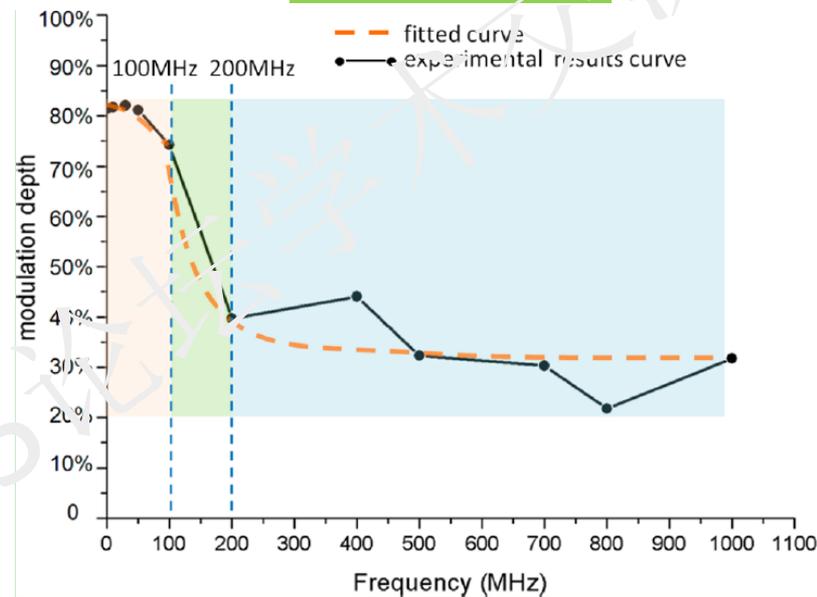
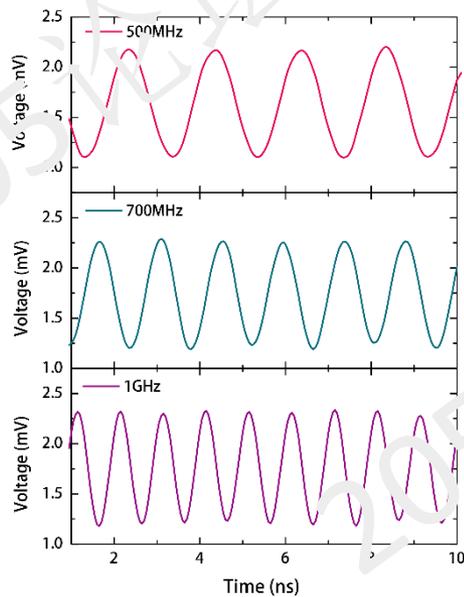
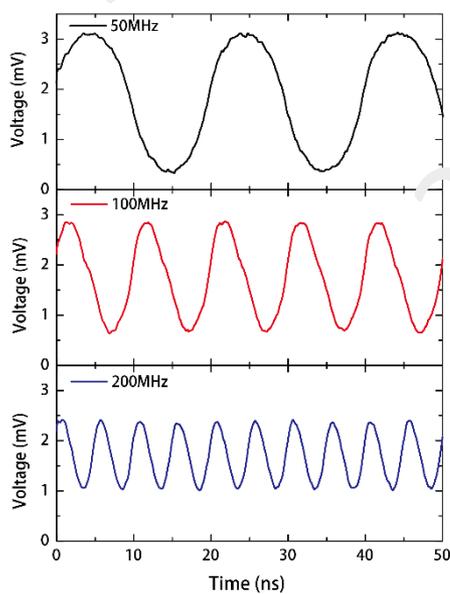


Packaged Modulator

# Dynamic test

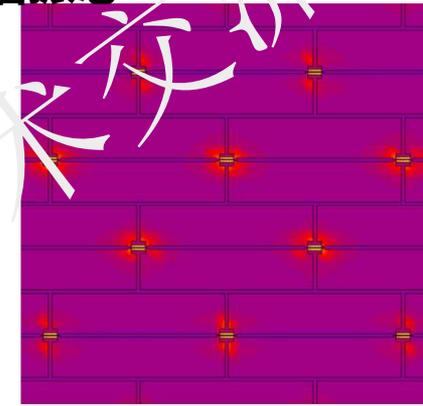
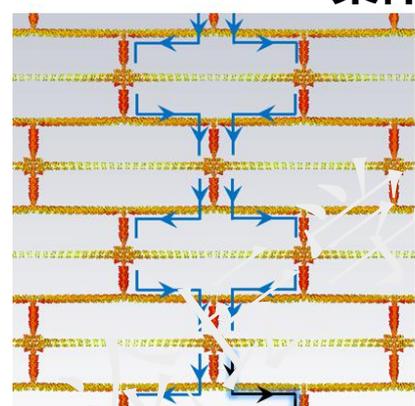
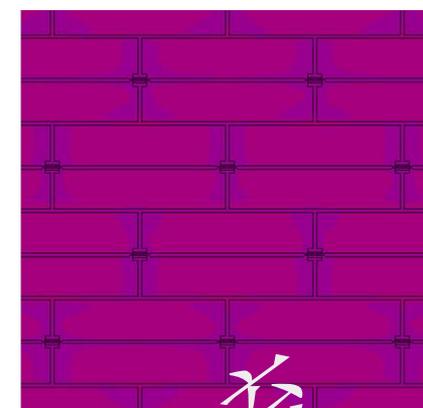
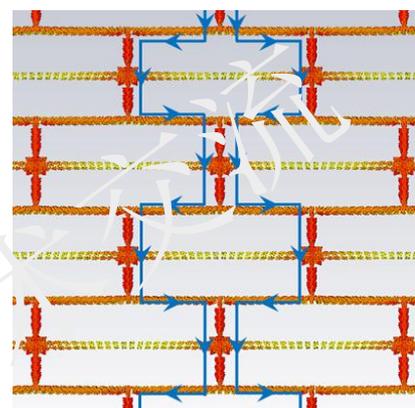
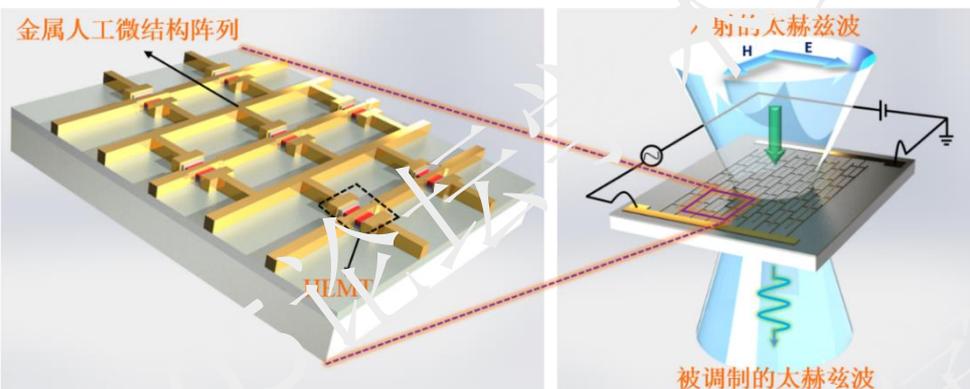


**Driving Circuit**



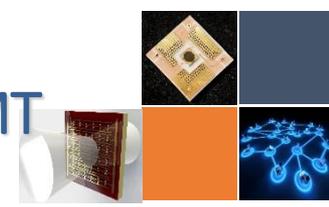
## 2. 运用meta单元与meta-surface阵列谐振转化实现幅度调制

### 运用控制二维电子输运实现阵列结构谐振态的转换



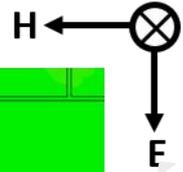
抑制了单元间的寄生，使得单元间寄生模式场强降低了1个数量级

# The stagger-netlike metamaterial array nested with GaN HEMT

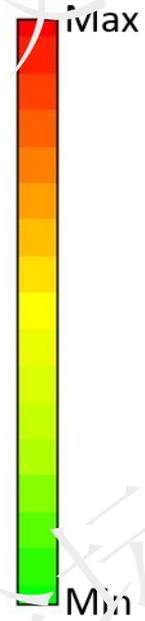
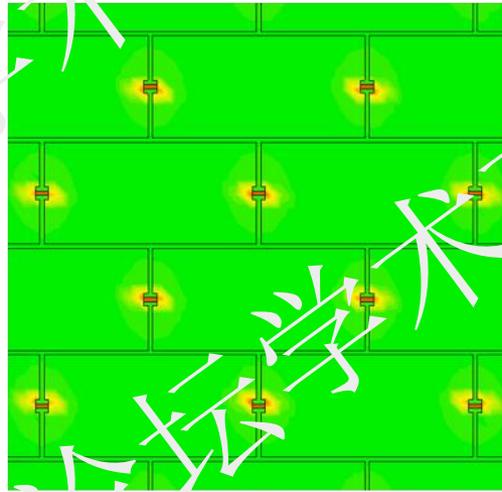


HEMT ON

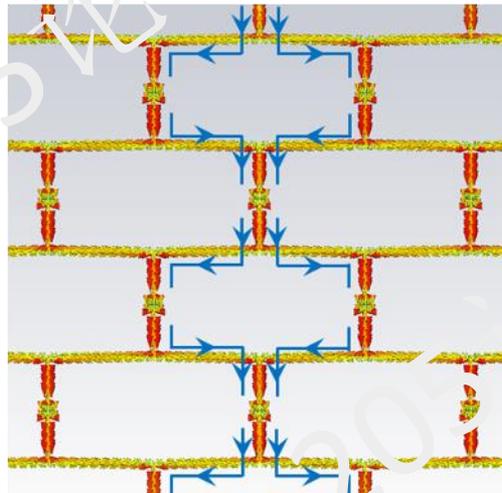
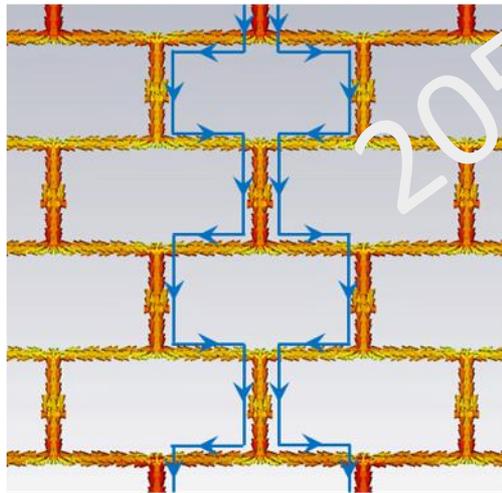
HEMT OFF



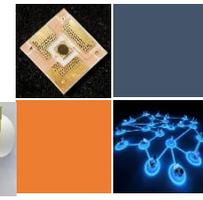
Electric fields



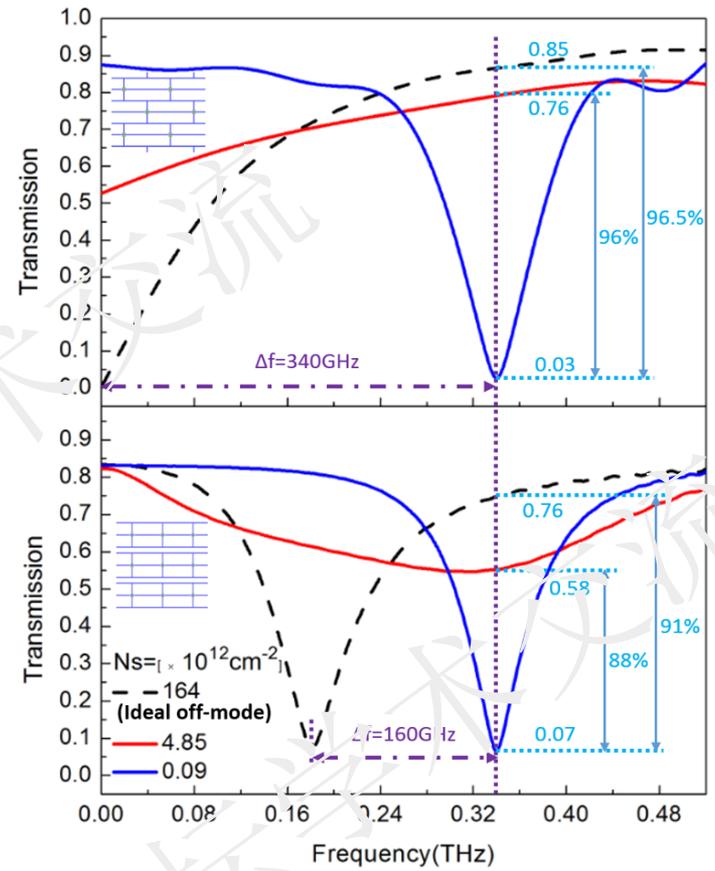
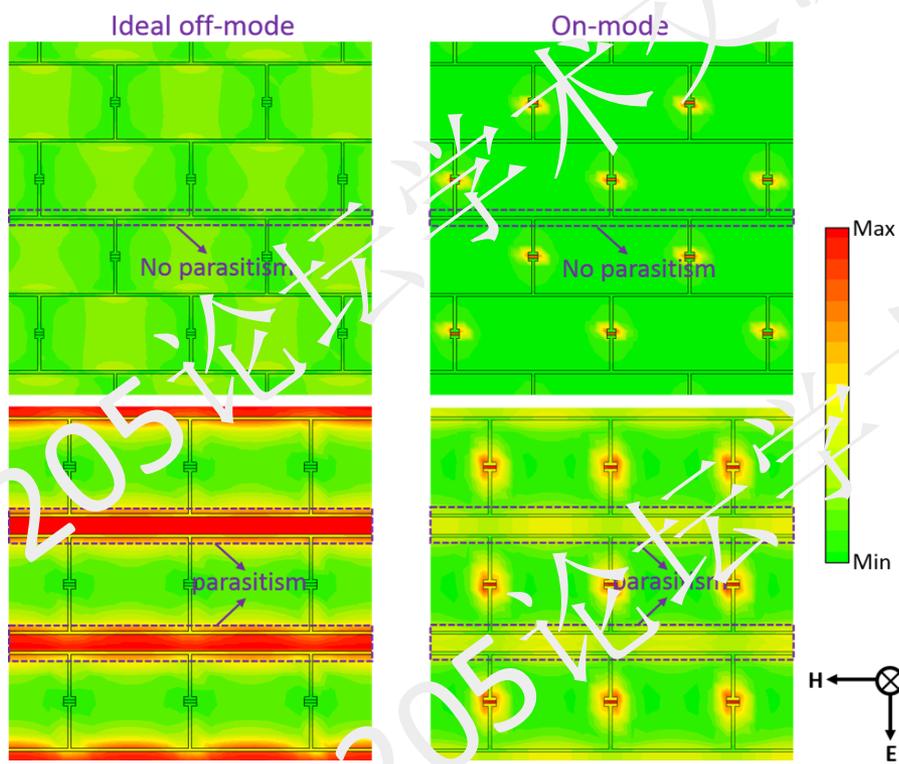
Surface current distributions



- ◆ In the high 2-DEG carrier density, the plates of the center gap in HEMT are connected to each other. The electric field of the whole array is weak. Surface current flows through the array continuously in periodic "S" path.
- ◆ When 2-DEG is depleted, the field focused on the central split gap plates. The surface current is changed to a discrete "S" path.

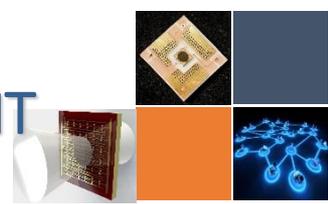


# The stagger-netlike metamaterial array nested with GaN HEMT

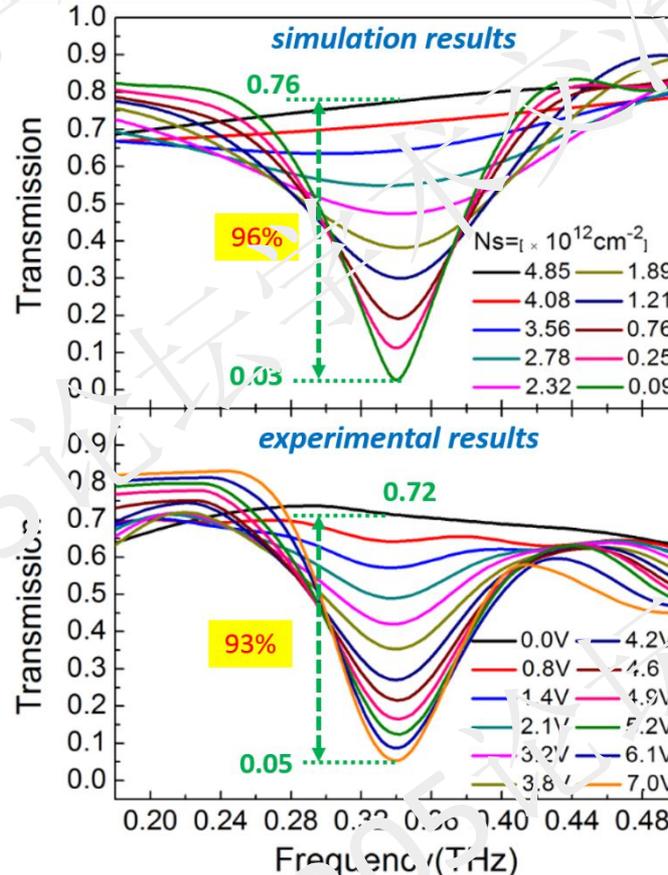
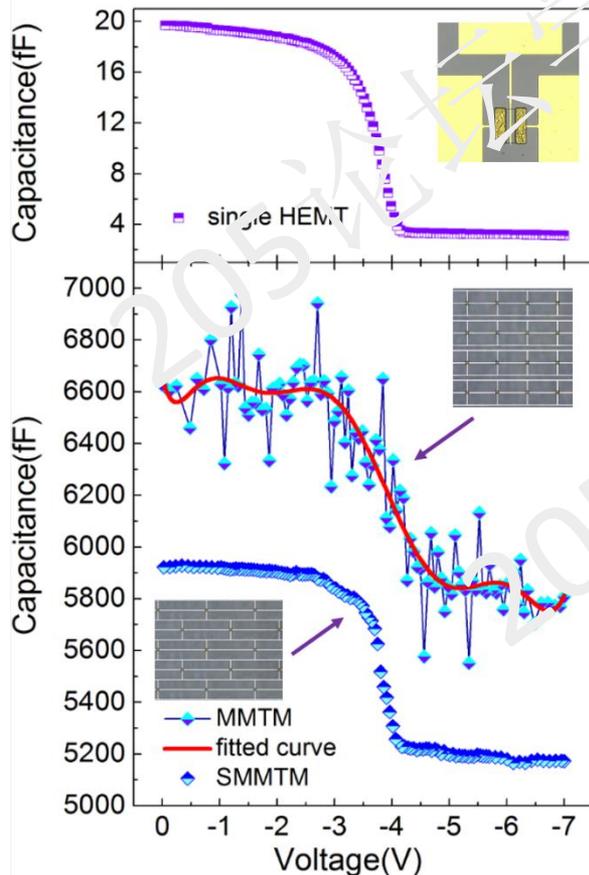


- ◆ Compared to the previous composite metamaterial structure, the drastic change of electric field in stagger-netlike metamaterial array occurs only in the center gap of HEMT, which is the functional region for modulating THz wave. In other areas, for example, between feeder lines, the existence of strong E-field and the apparent fluctuation of the field intensity mean parasitism.
- ◆ Due to the difference in mode conversion, the  $\Delta f$  enlarges from 160GHz to 340GHz. In theory, the modulation depth is increased by 8 percentage points, up to 96%.

# The stagger-netlike metamaterial array nested with GaN HEMT

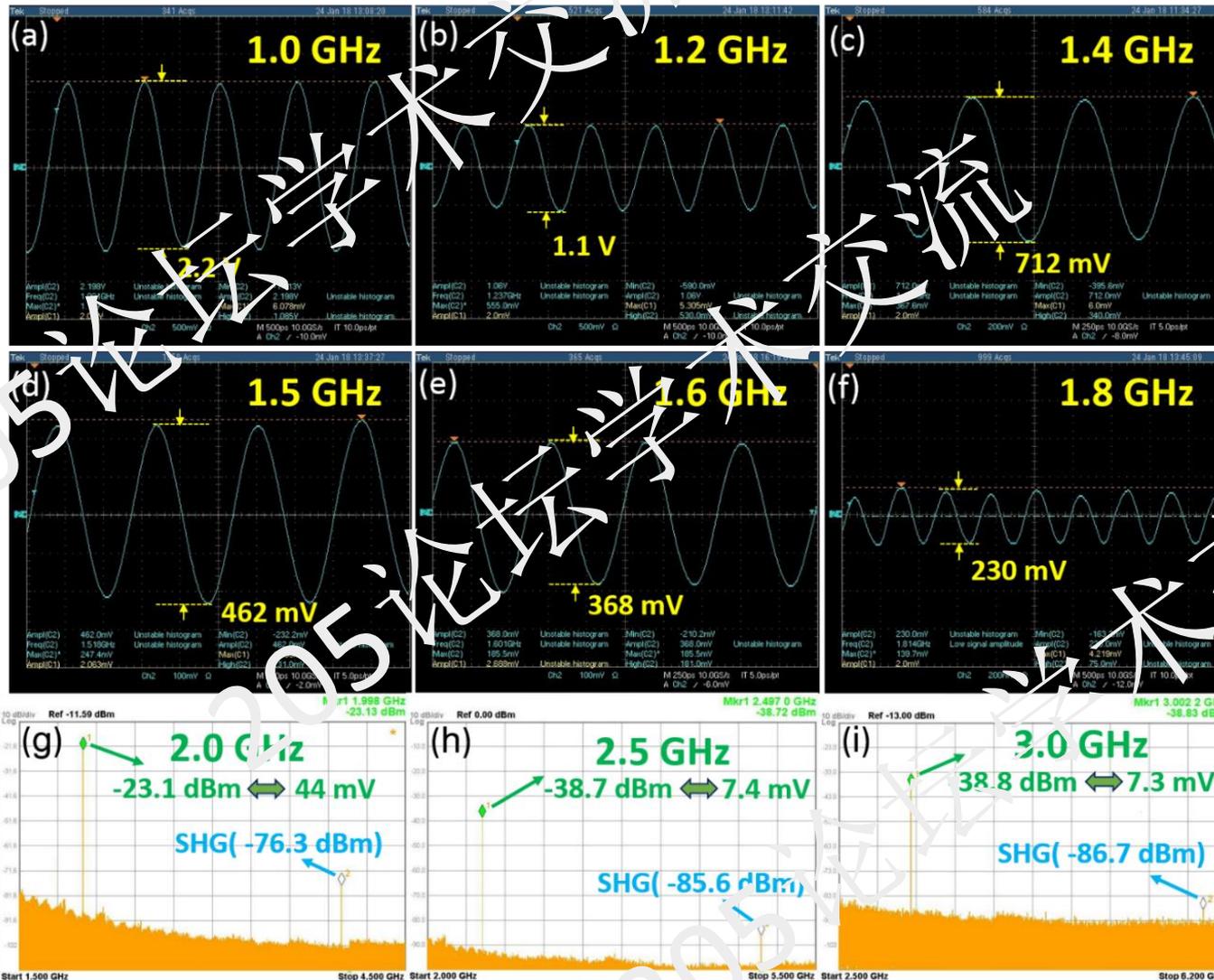
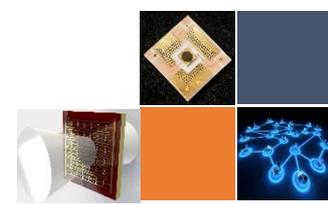


## Static THz experiments



- Due to the interference of parasitic factor, the C-V characteristic curve of MMTM is chaotic, although the fitted curve is similar to the C-V relation of single HEMT. The C-V relation of SMMTM is perfectly consistent with single HEMT's.
- THz-TDS test results show that the modulation depth of SMMTM is as high as 93%, which is very close to the simulation results.

# Dynamic THz experiments



- ◆ All of the detected signals are standard sinusoidal waveforms. Due to the limitation of oscilloscope bandwidth, the 2-3 GHz modulation signals are tested by spectrum analyzer.

### 3. 采用模式耦合meta-surface阵列实现相位调制

从克莱默-克朗尼格(K-K)关系出发:

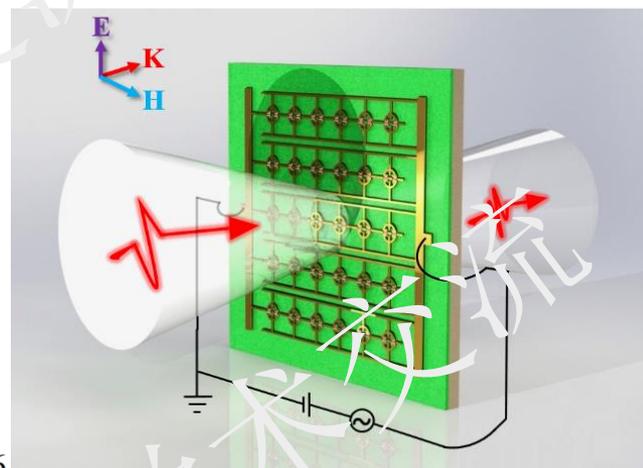
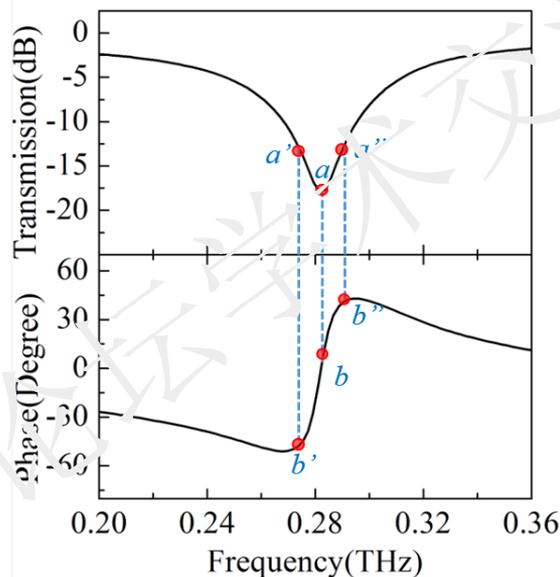
得到具有因果性的响应函数的实部和虚部之间的联系

响应函数

$$G(\omega) = G'(\omega) + iG''(\omega)$$

$$G'(\omega) = \frac{2}{\pi} P \int_0^{\infty} \frac{\omega' G''(\omega')}{\omega'^2 - \omega^2} d\omega'$$

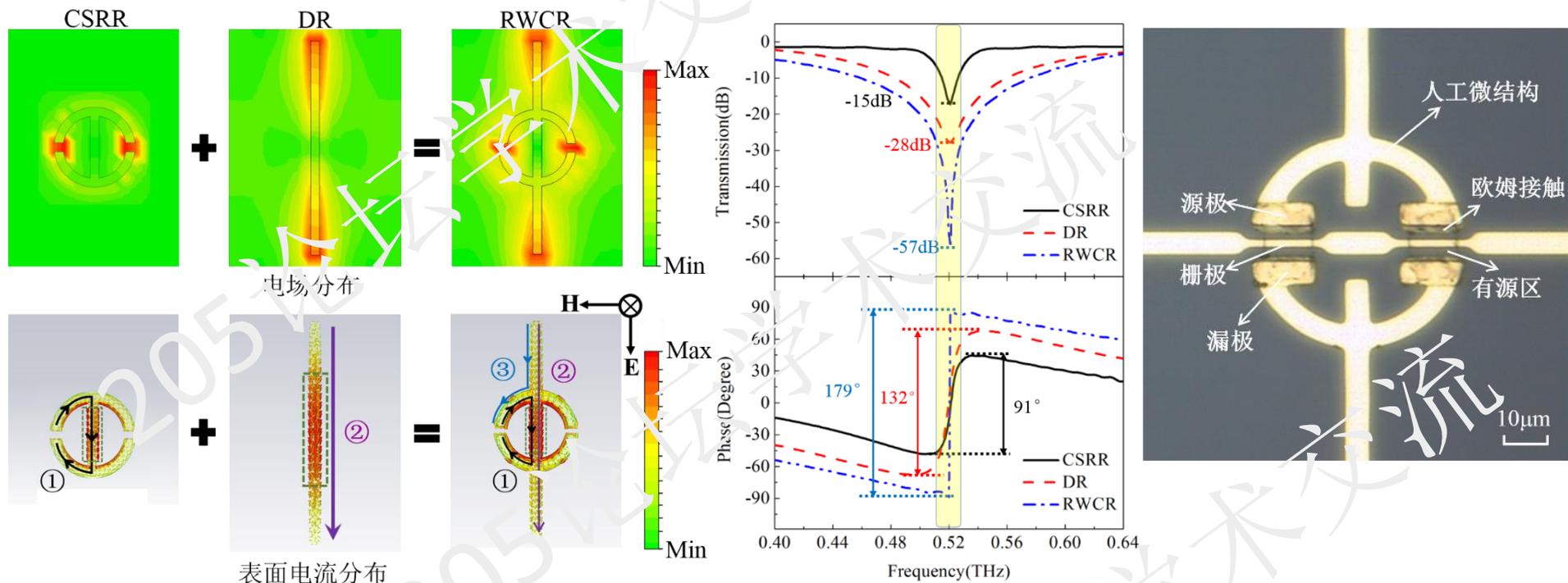
$$G''(\omega) = -\frac{2\omega}{\pi} P \int_0^{\infty} \frac{G'(\omega')}{\omega'^2 - \omega^2} d\omega'$$



幅度色散曲线的谐振峰对应着相位跳变。增大谐振强度可提高透射相位跳变量，进而提高调相位调控量。

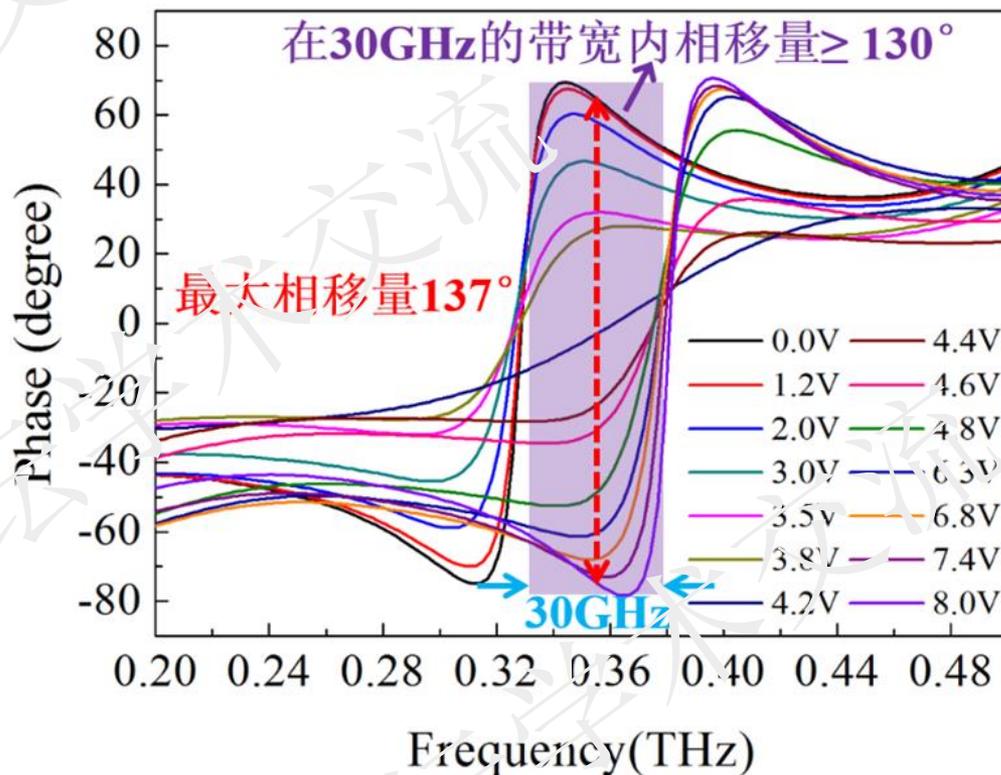
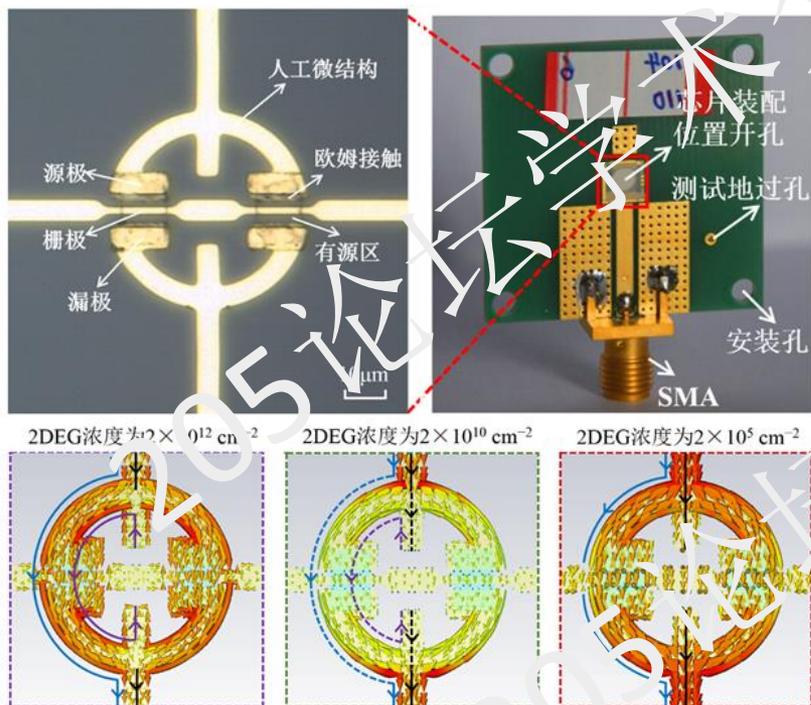
### 3. 采用模式耦合meta-surface阵列实现相位调制

#### 采用二维电子调控模式耦合强度



通过二维电子调控偶极谐振和LC谐振的相互间耦合强度，控制相位。

### 3. 采用模式耦合meta-surface阵列实现相位调制



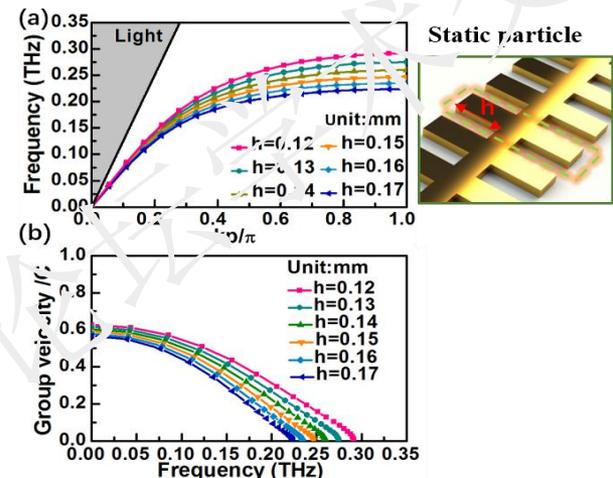
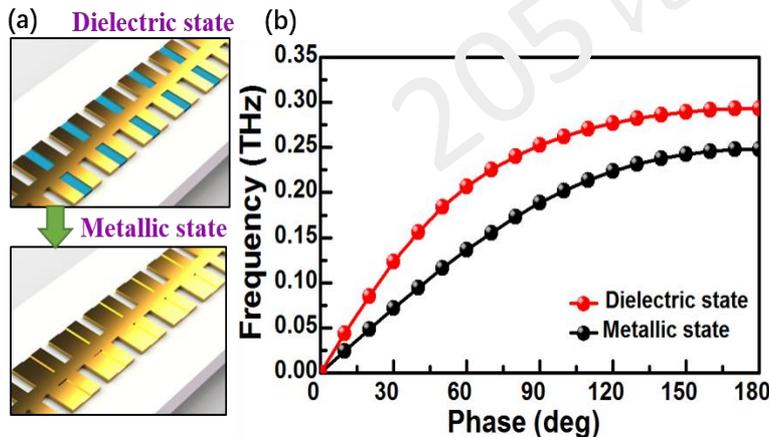
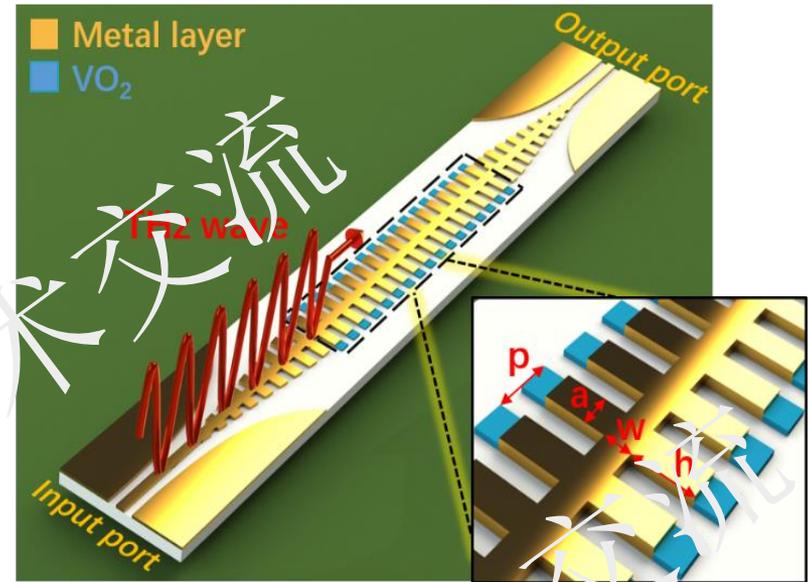
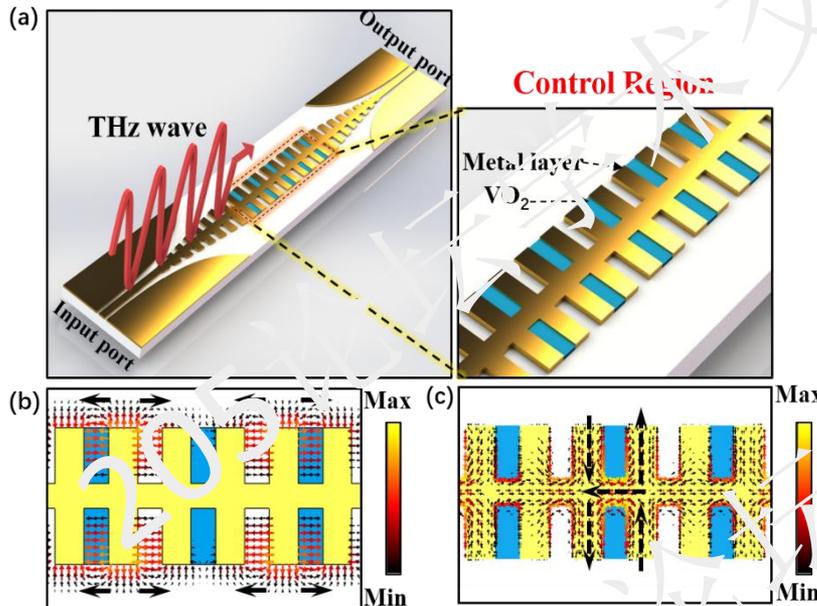
实现了对自由空间传输的太赫兹波  
单层透射式130度以上的相位调控，并且带宽大于30GHz

# 提纲

- 1 太赫兹动态调制器件研究现状
  - 2 太赫兹阵列调制器件-metasurface
  - 3 **太赫兹片上调制器件-metachip**
  - 4 太赫兹调制器件发展的挑战和思考
-

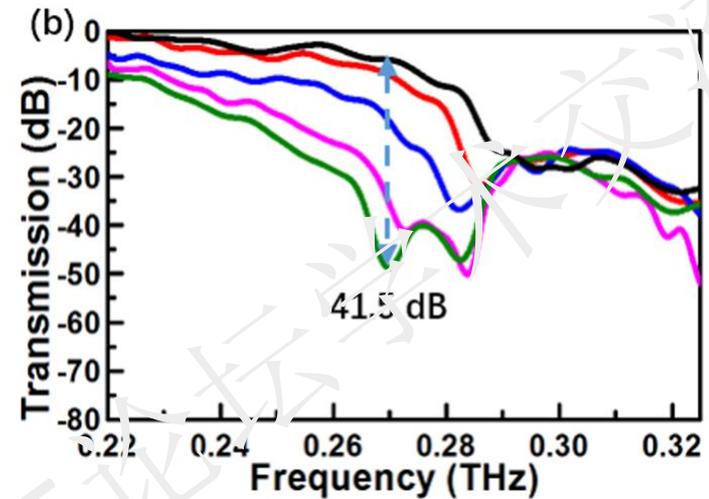
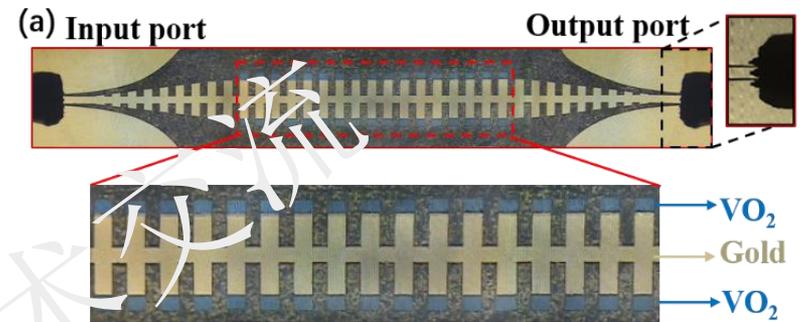
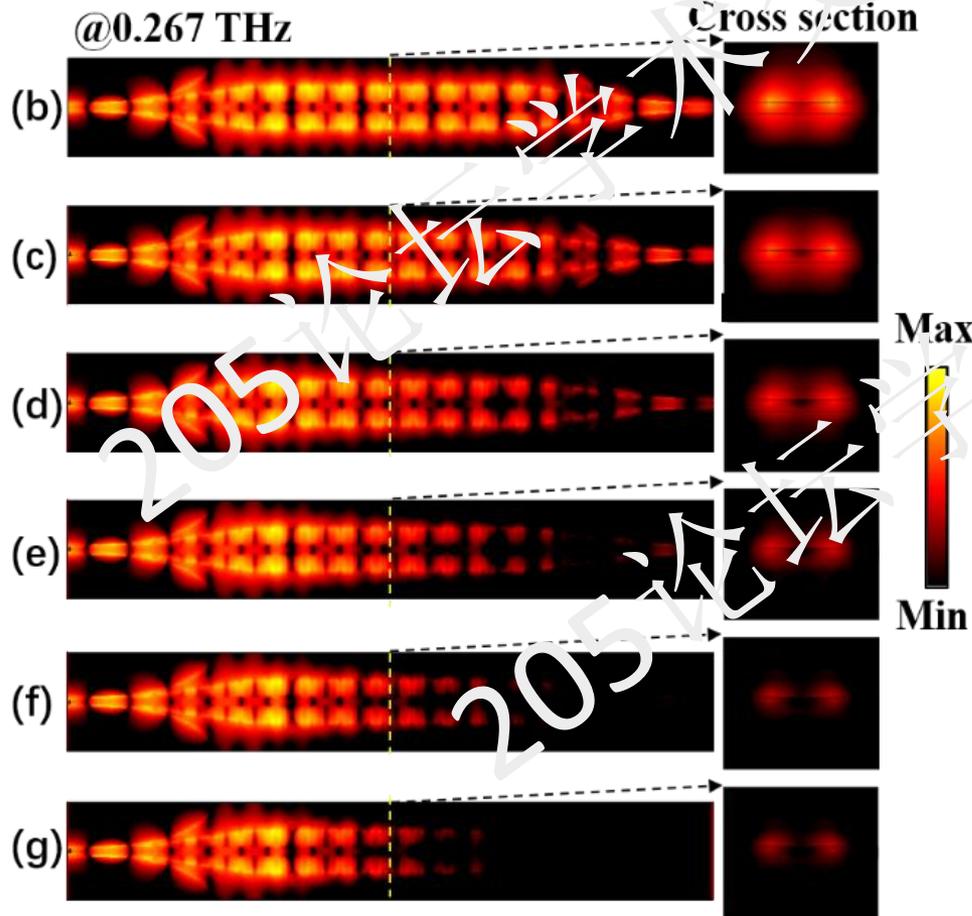
# 太赫兹片上调制器

早期思路：动态材料与片上周期阵列结合如：表面波+氧化钒



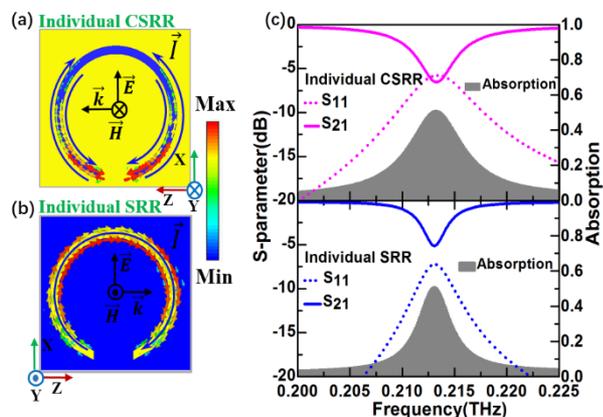
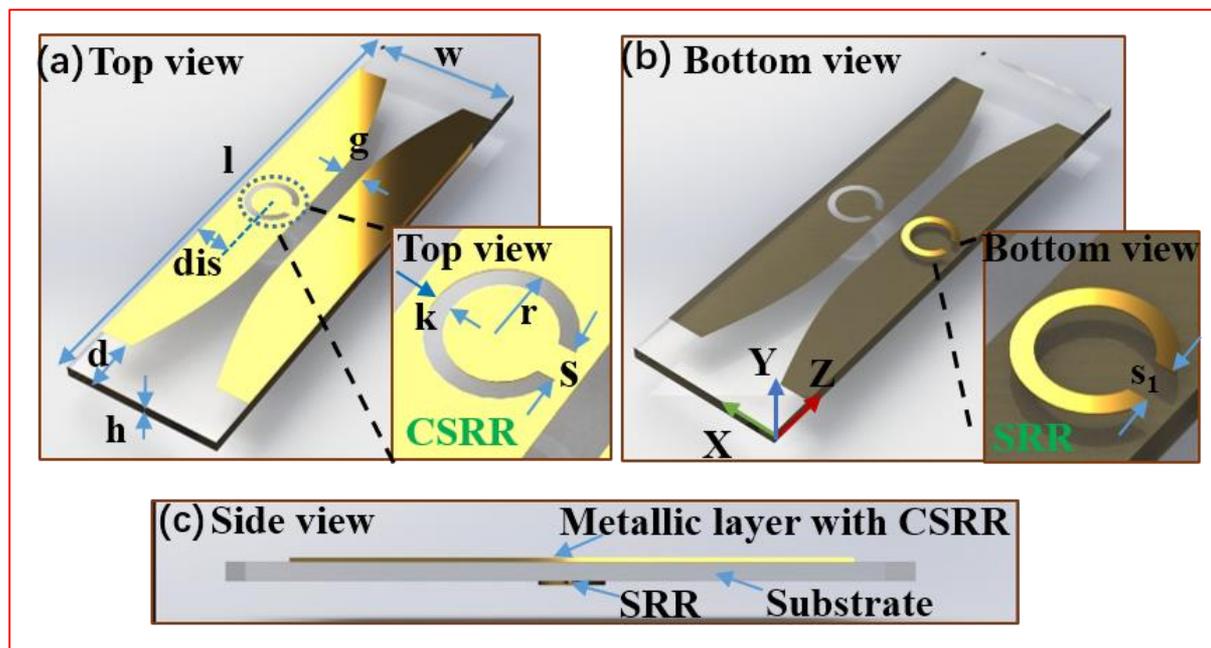
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早期思路：动态材料与片上周期阵列结合如：表面波+氧化钒



# 太赫兹片上meta-chip调制器

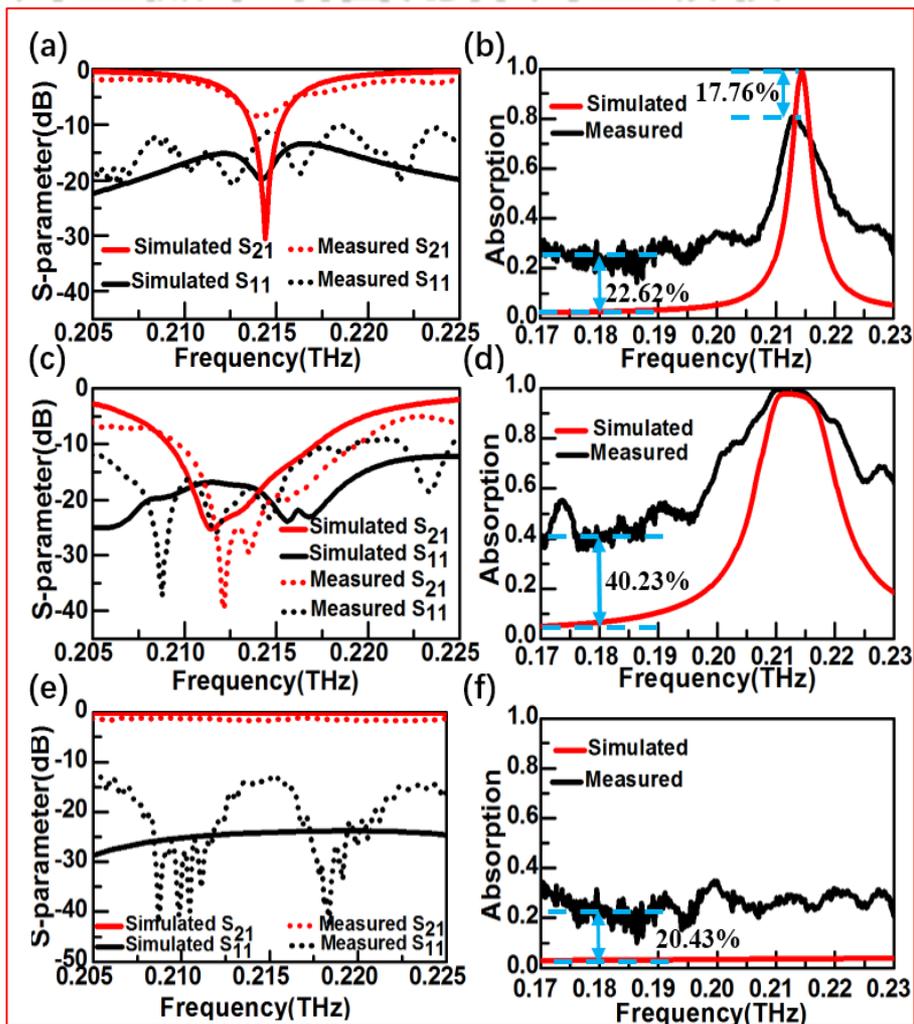
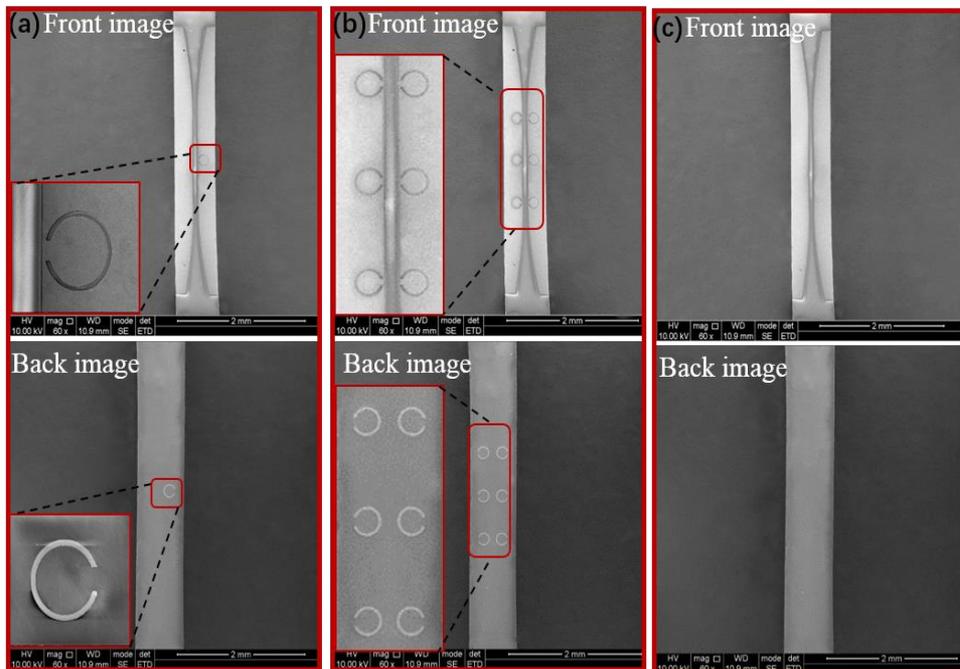
思路发展：微结构谐振单元与片上微带结合用作片上吸收



- 通过将一系列互补金属超原子对排列在鳍线传输线两侧，由于金属超原子对间电磁谐振的相互干扰，传输的太赫兹波被高效吸收。

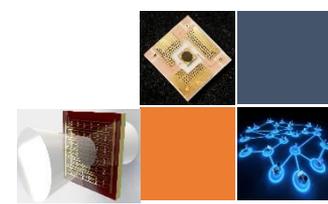
# 太赫兹片上meta-chip调制器

## 思路发展：微结构谐振单元与片上微带结合用作片上吸收



实验结果显示该片上调制器在0.207-0.218THz吸收率可以达到93%以上

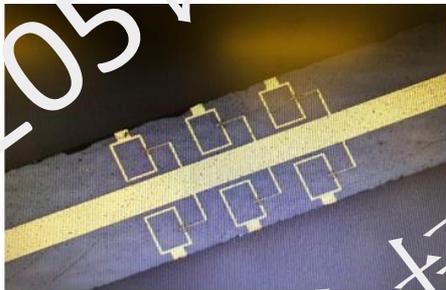
# 太赫兹片上meta-chip调制器



思路成形：有源微结构谐振单元与片上微带结合

The microstrip line + dynamic active meta-modulation units

The modulator on chip with a modulation rate greater than 10GHz were developed for 0.22thz, 0.34thz



■ 0.22THz 3-row modulation units



■ 0.34THz two control modulation unit



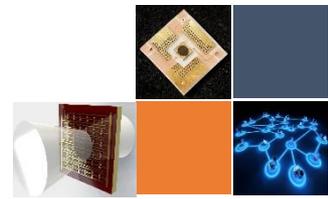
■ 0.22THz diodes modulation units



■ 0.22THz diodes modulation units

■ Advantage: fewer modulation units, easier impedance matching and integration.

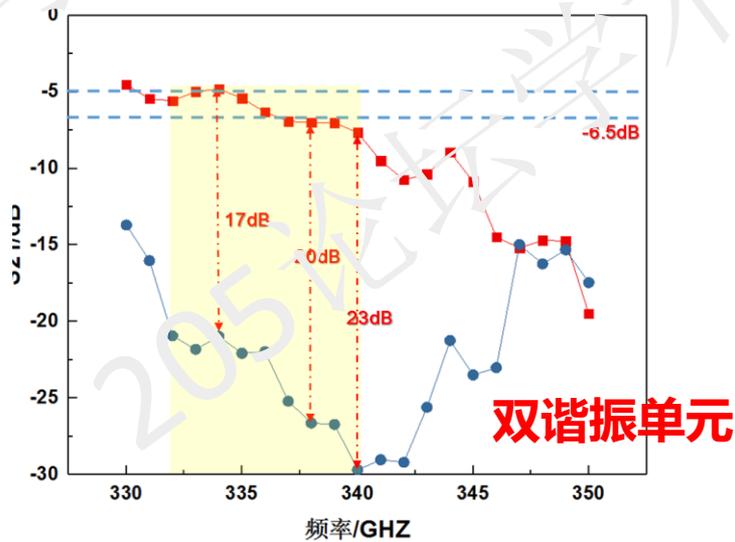
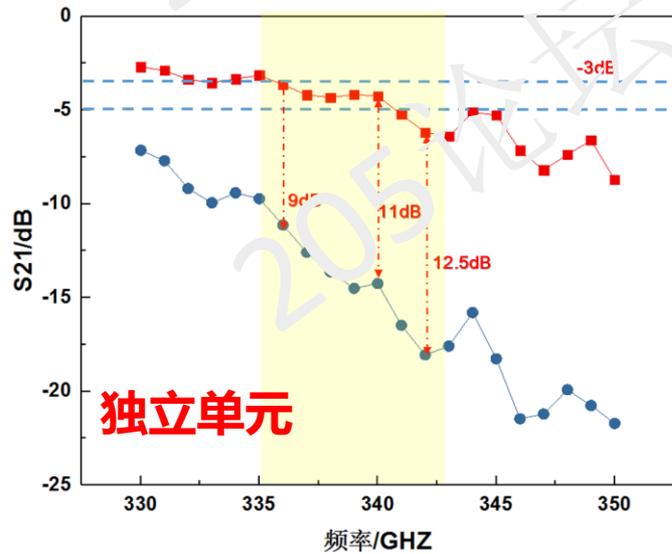
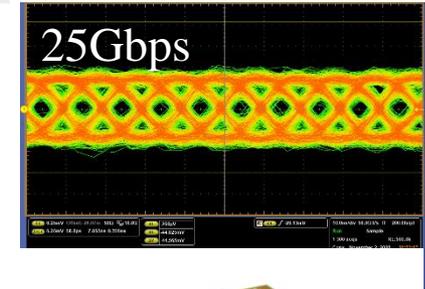
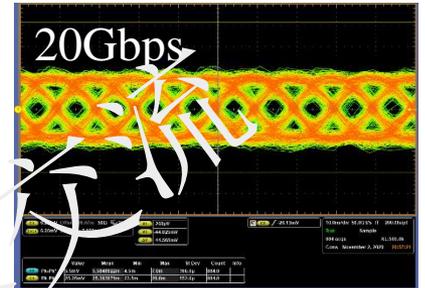
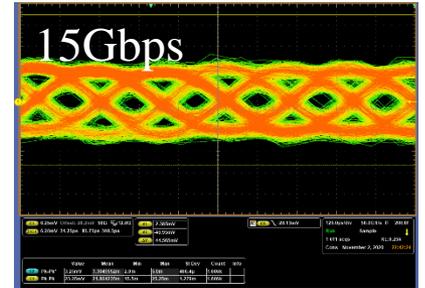
# 太赫兹片上meta-chip调制器



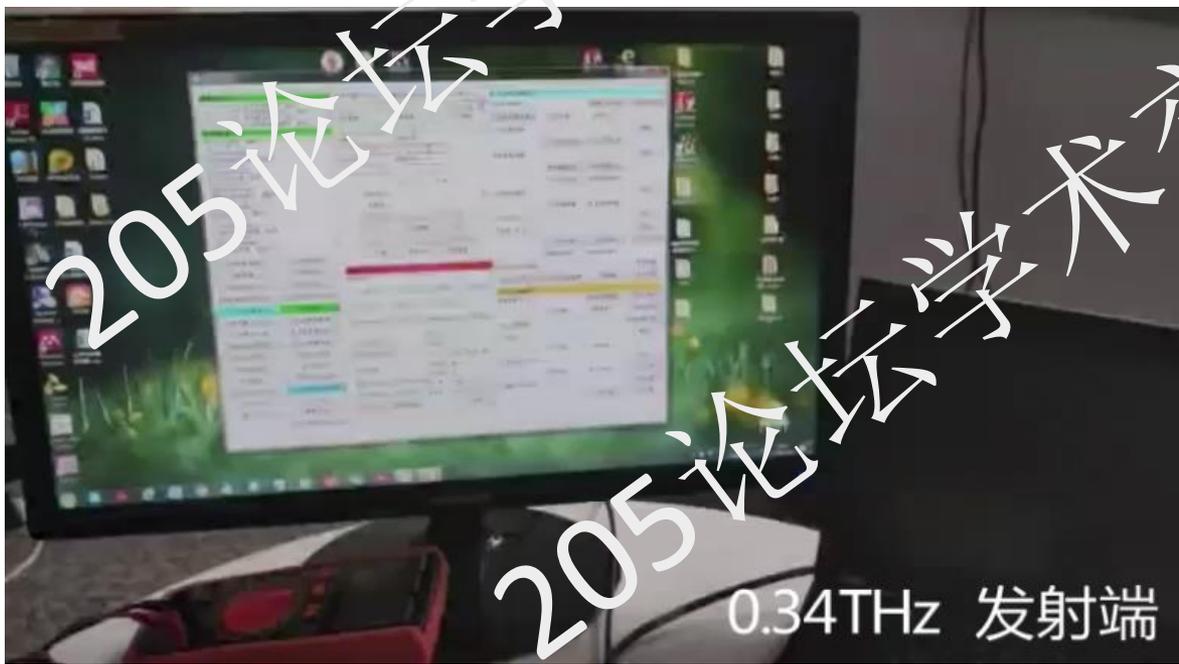
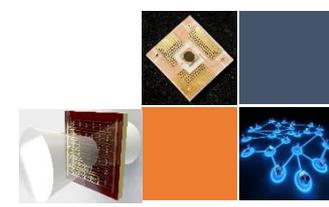
有源微结构导通-形成片上微扰



有源微结构断开-形成片上谐振



# 太赫兹直接调制通信系统2.0 (2018-)



# 提纲

1

太赫兹动态调制器件研究现状

2

太赫兹阵列调制器件-metasurface

3

太赫兹片上调制器件-metachip

4

**太赫兹调制器件发展的挑战和思考**

## 1. 器件发展思考

**更高速率：目前已经突破25Gbps，朝着100Gbps发展**

**结合系统层面发展：兼顾带宽利用率，发展幅相共调的高阶直调**

## 2. 太赫兹通信架构思考

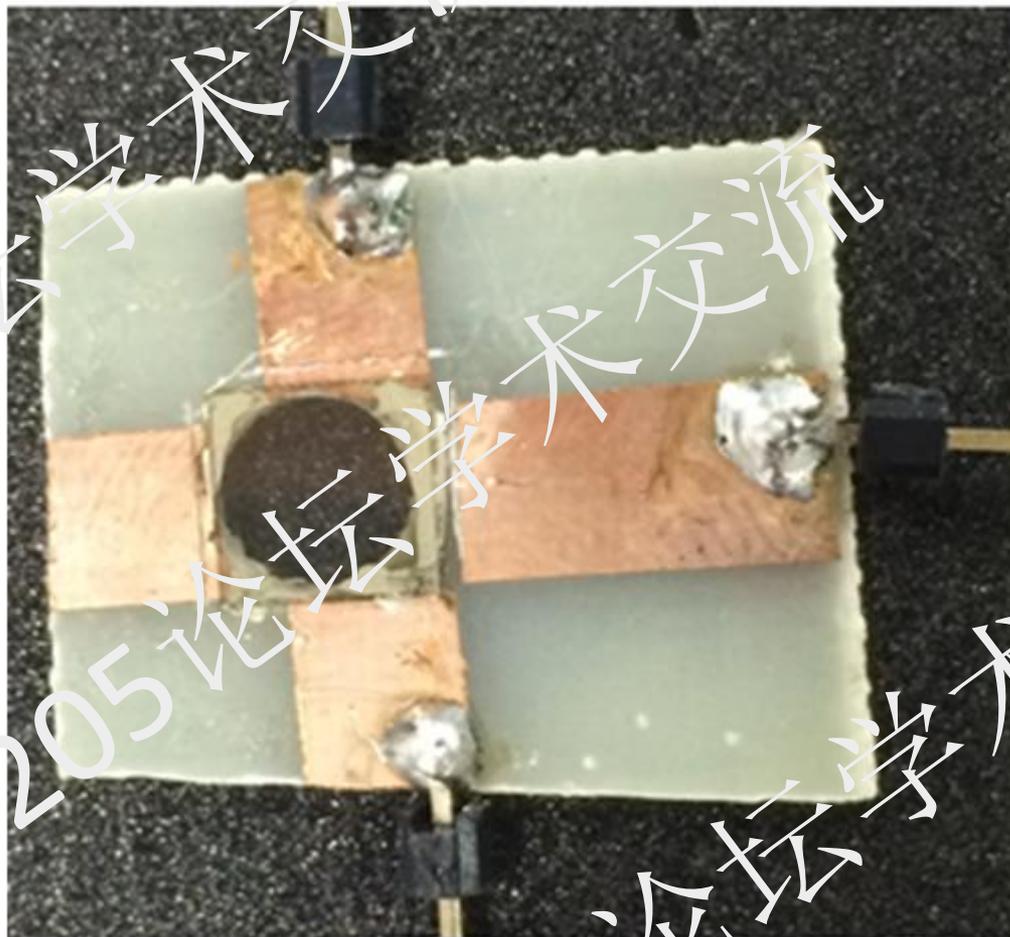
**多路数字编码高阶直接调制通信体制**

## 3. 太赫兹直调解调端思考

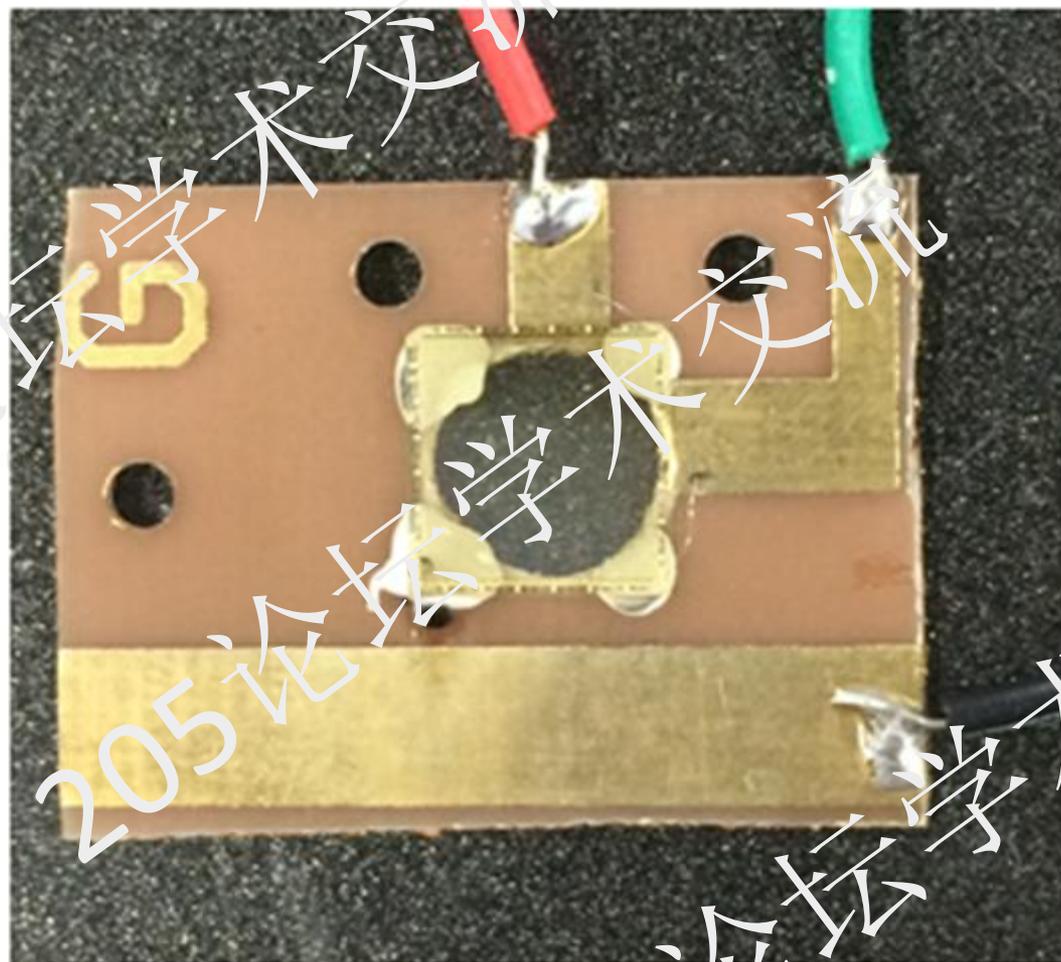
**目前10Gbps以上的直接调制OOK通信，最大限制已经不再是调制器限制，最大限制性问题在于解调技术：**

- **如何形成与之相匹配的基带电路是问题之一**
- **如何发展超宽带低噪放、中频放大器成为限制其发展的问题之二**

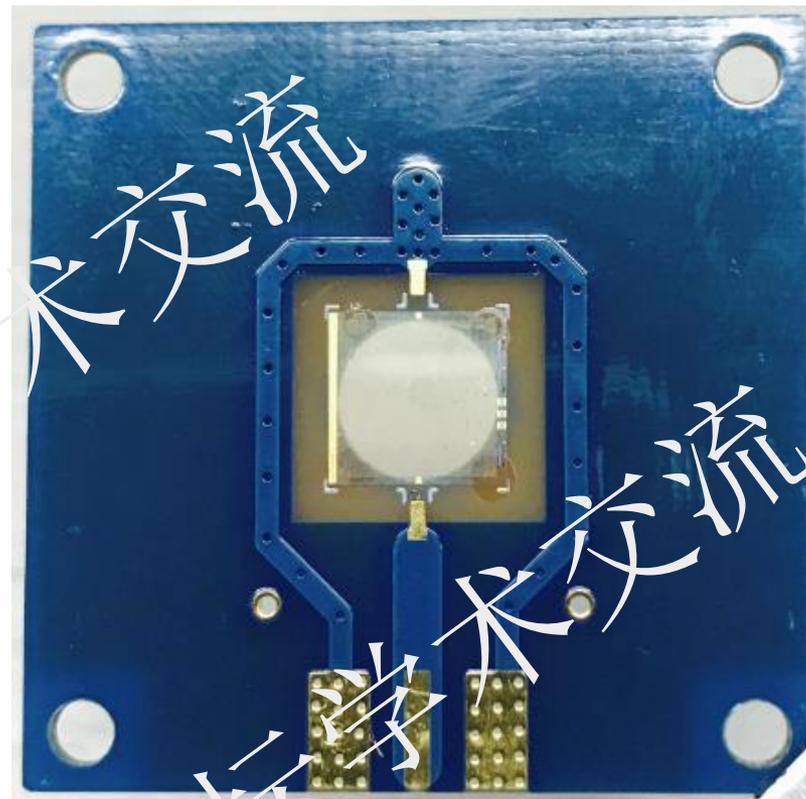
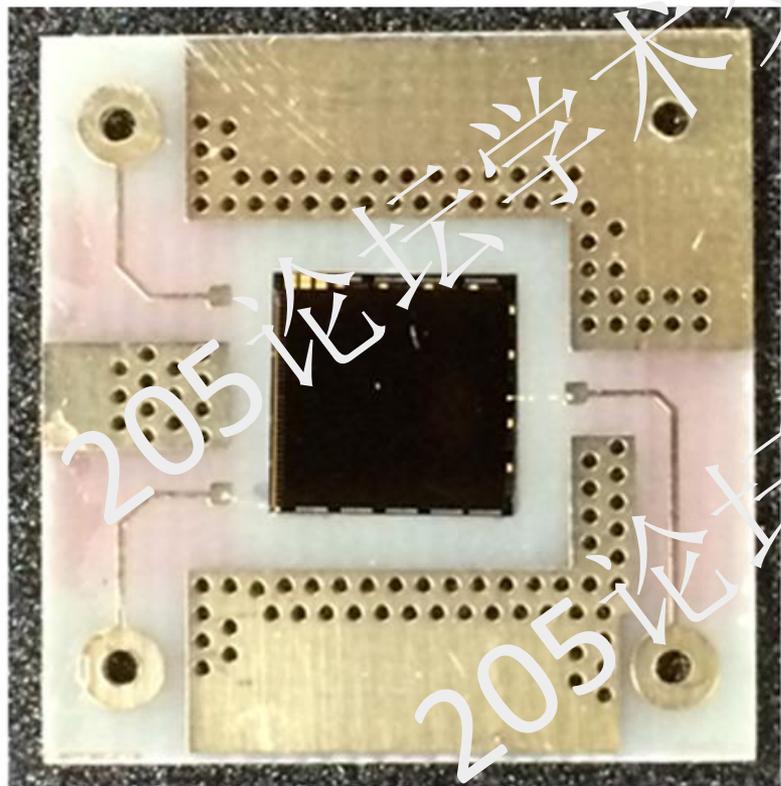
2011-2012年花了一年做的太赫兹调制器—100kHz



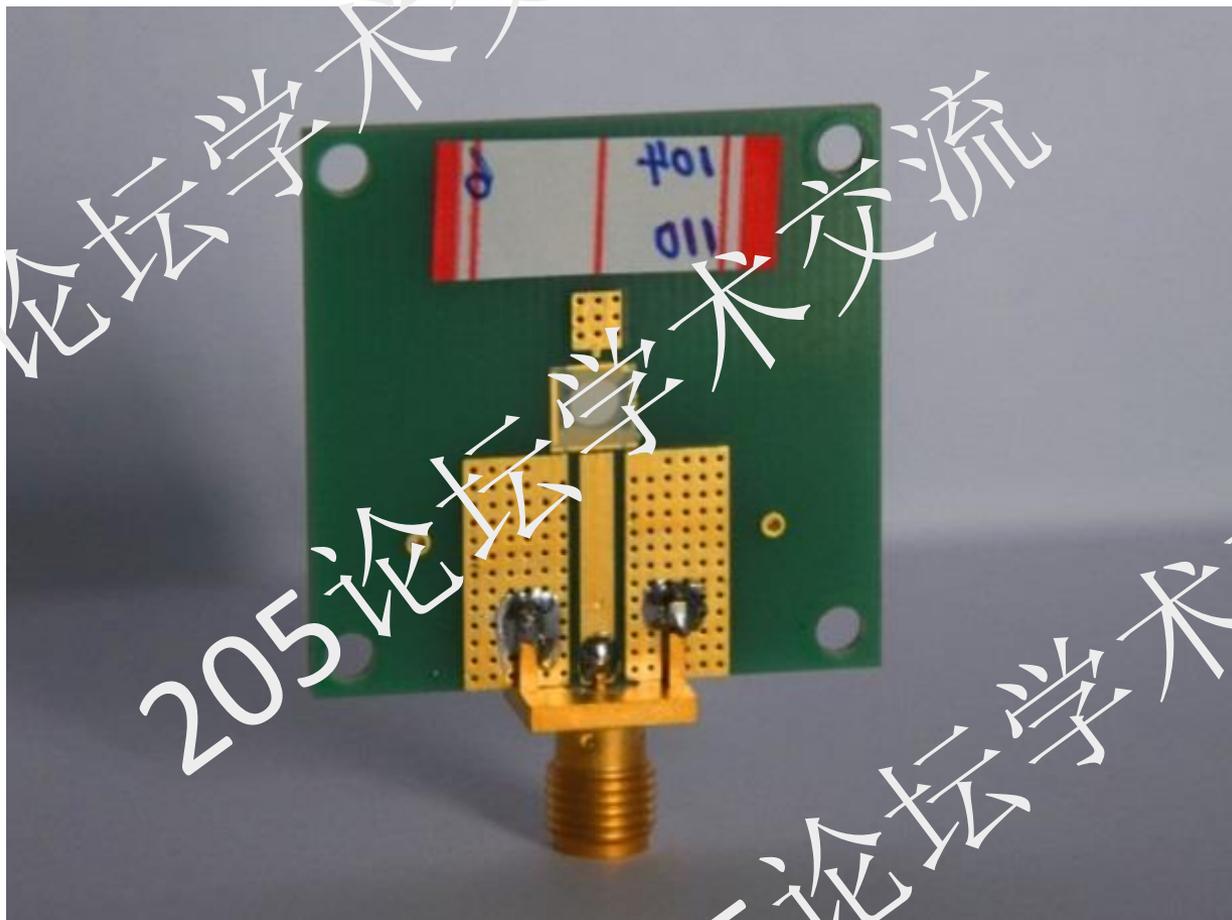
# 2012-2013 太赫兹调制器2.0—1MHz



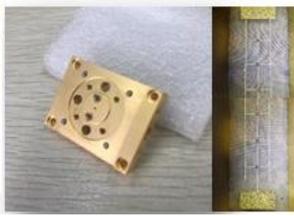
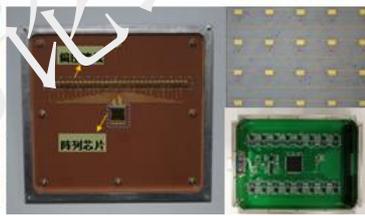
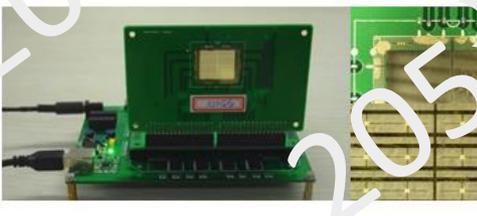
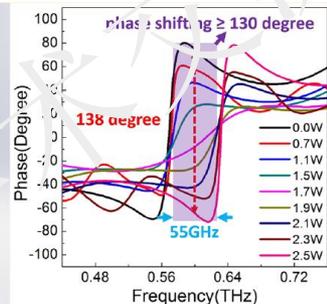
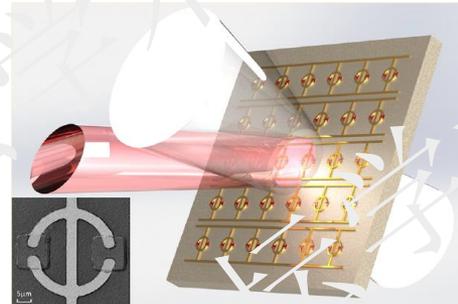
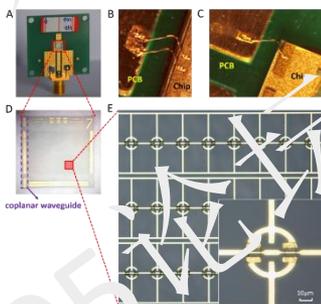
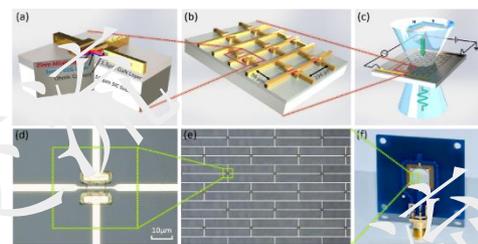
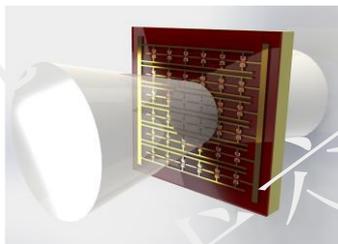
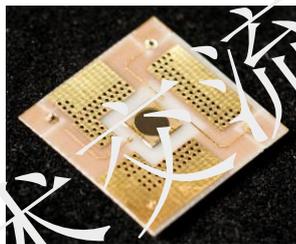
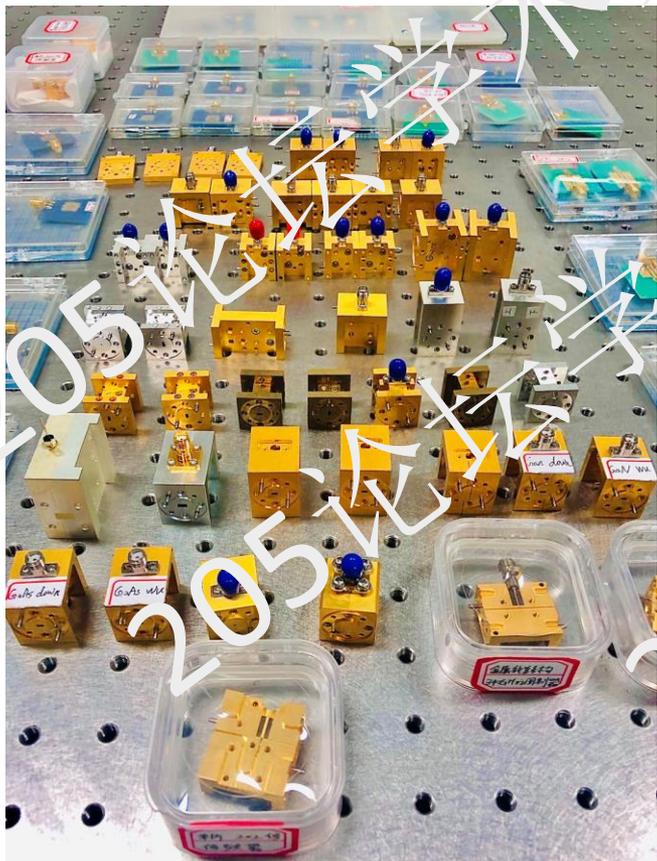
# 2013-2015 太赫兹调制器3.0—1GHz



# 2015-2017 太赫兹调制器4.0—3GHz



# 2018-2020 太赫兹调制器突破25Gbps



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- Yuncheng Zhao , Yaxin Zhang\*, *ACS Photonics* **5**, 3040,2018
- Ting Zhang, Yaxin Zhang\*, *IEEE Ele. Dev. Lett.*,40, 1844, **2019**.
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