Increased terahertz emission from monolayer graphene with field enhancement effect

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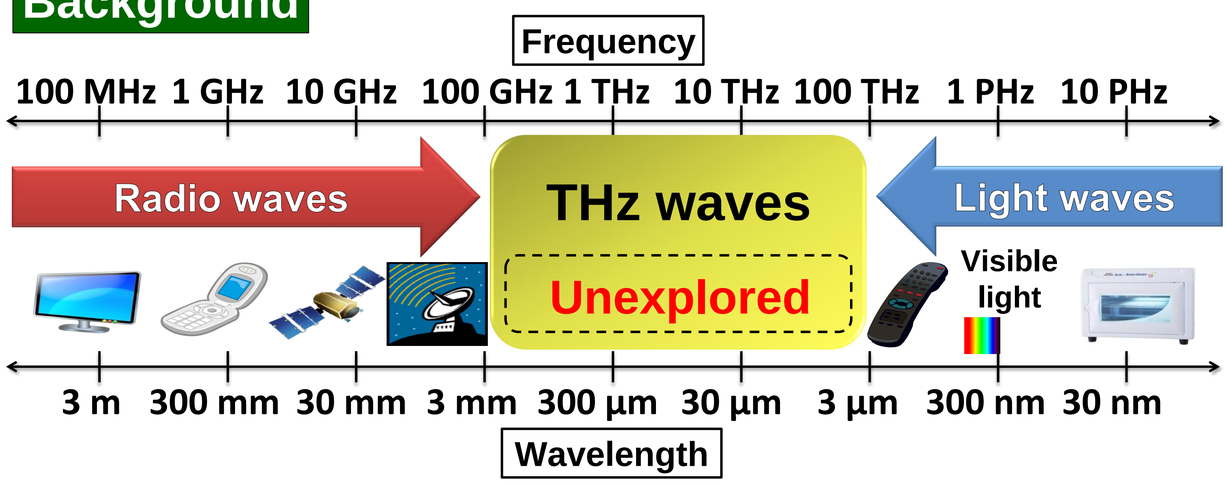
Background



Terahertz gap

1. Maximum operating frequency of electronic devices
   ➡ Limited by electron velocity
2. Minimum operating frequency of optical devices
   ➡ Restricted by thermal noise at room temperature

We are currently developing THz devices by using a novel operating principle

Operation principle

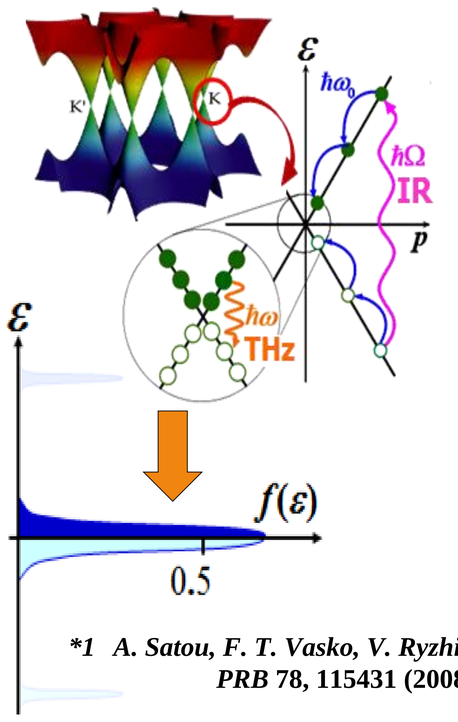
Photo-excited graphene

Irradiation of graphene with infrared laser

Formation of population inversion from generated electron-hole pairs

Emission of THz waves by recombination

Amplification of 1 – 10 THz waves

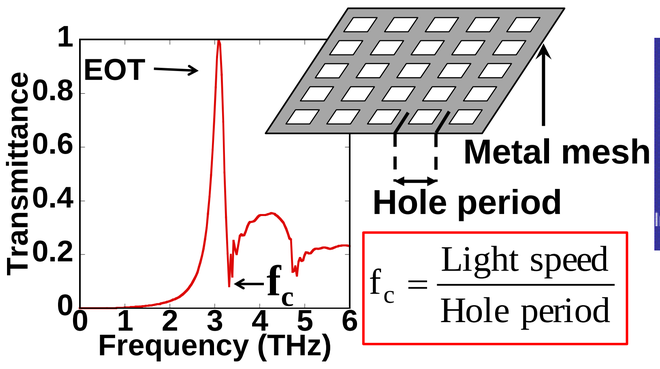


**1 A. Satou, F. T. Vasko, V. Ryzhii, PRB 78, 115431 (2008)*

Properties of metal mesh structure

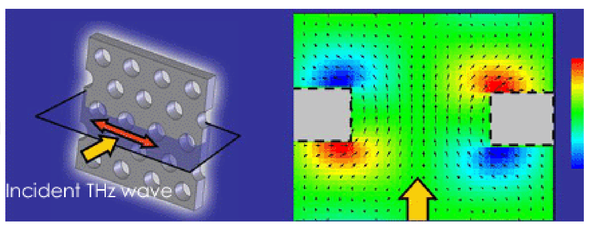
- Extraordinary optical transmission (EOT)
- Field enhancement effect caused by spoof surface plasmon polaritons (SPPs)

Transmission characteristics of metal mesh structure



$$f_c = \frac{\text{Light speed}}{\text{Hole period}}$$

Field enhancement effect due to SPPs[*2]



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Objective

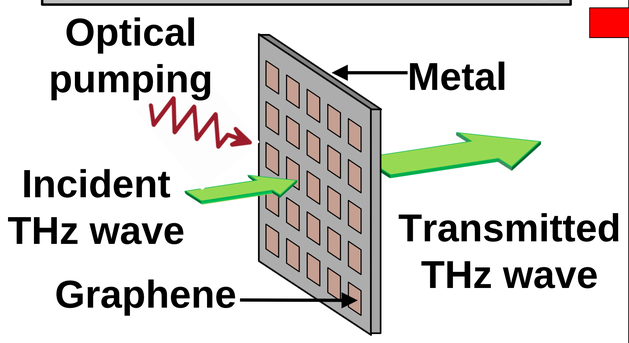
Improving our original THz amplifier to increase THz emission

Concept of THz amplifier

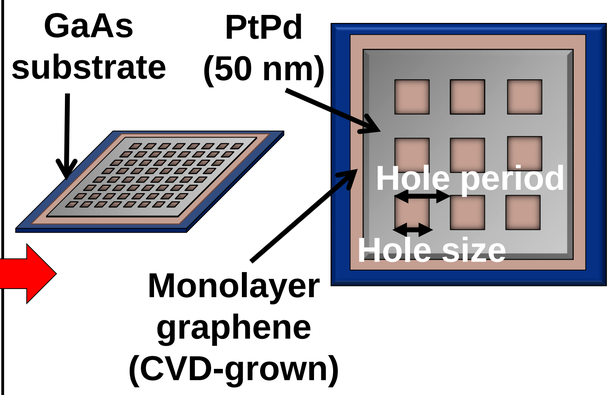
Graphene (THz wave gain medium)

+

Metal mesh structure (field enhancement & EOT)

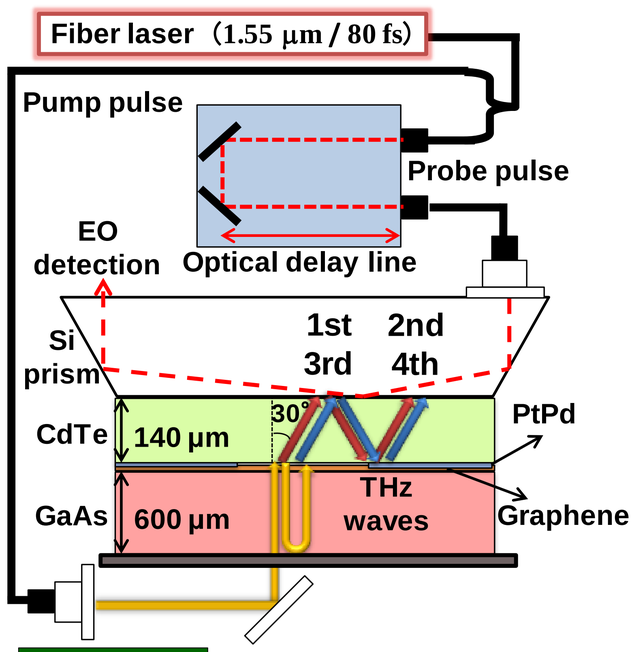


Construction of THz amplifier (GaAs + Metal + Graphene)



	Hole period	Hole size
New	20 µm	10 µm
Original	60 µm	30 µm

Measurement system



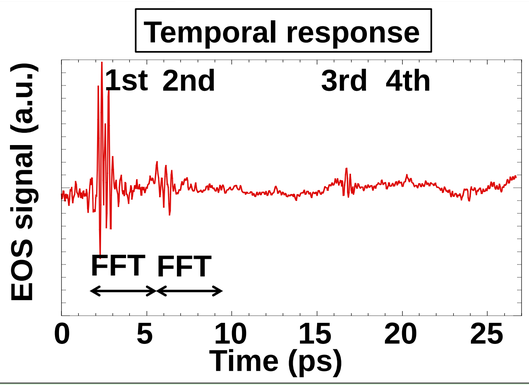
Reflective Electro-Optic Sampling

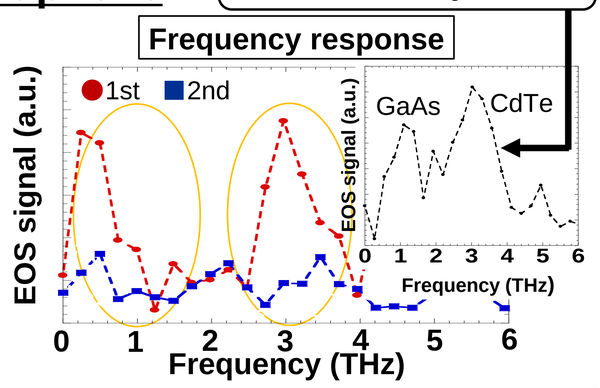
- **Pump pulse**
  - ✓ Photoexciting the sample and CdTe crystal
  - ✓ Generating THz waves in GaAs substrate and CdTe crystal by optical rectification
- **Probe pulse**
  Sensing electric field by electro-optic crystal (refractive index change due to electric field)

Results

GaAs + Graphene

Spectrum of THz waves generated in GaAs and CdTe crystals

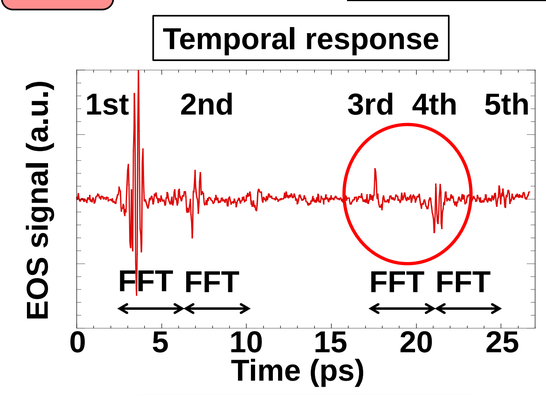


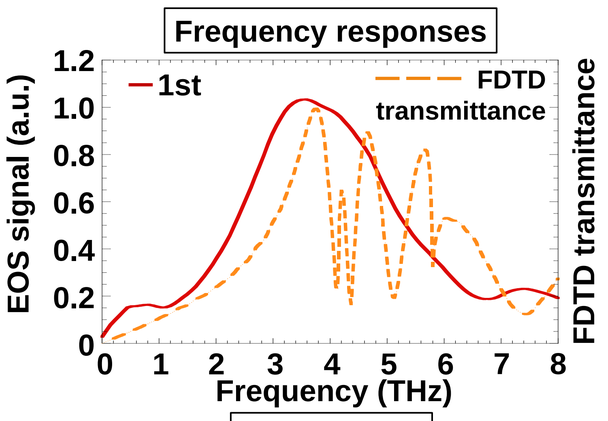


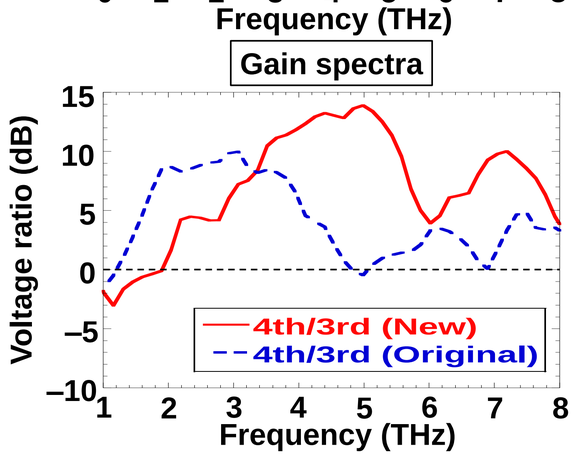
- ✓ 1st wave was similar to THz waves generated in GaAs and CdTe crystals
- ✓ 3rd and 4th waves were hardly observed
- ✓ Amplification was not achieved

GaAs + Metal + Graphene

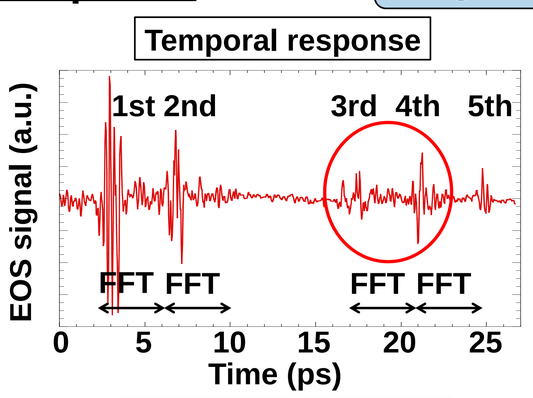
New

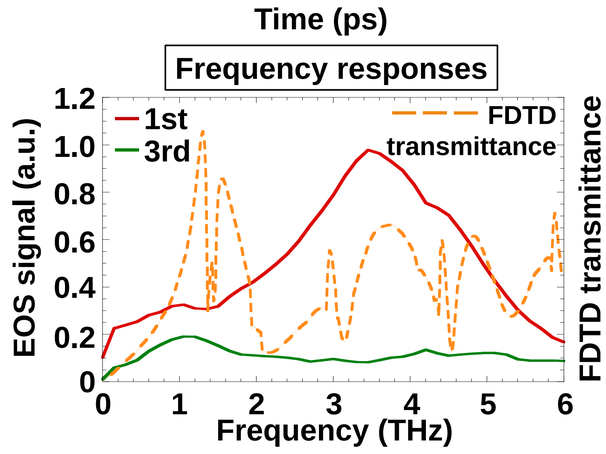






Original





- ✓ Despite the same reflection process as the 1st and 2nd waves, the 4th wave was significantly increased in each amplifier
- ✓ The FDTD transmittance of metal mesh matched the generated THz spectrum of new amplifier
- ✓ Amplification of new amplifier is larger than that of original amplifier

These observations suggest

(1) The presence of population inversion in graphene
(2) Field enhancement due to SPPs (buildup time: several picosec)
(3) Bragg radiation

Conclusion

- ✓ Significantly enhanced THz emission from new amplifier compared to original one
- ✓ The increased voltage ratio at 3 – 6 THz was caused by the adjustment of the resonance frequency of the metal mesh to the population inversion frequency
- ✓ The combined effect of population inversion in graphene and field enhancement enables the amplification of THz waves

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