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# A Theoretical Study of Comparison of Graphene, Superconductors and Metals as Conductors for Meta Materials and Plasmonics

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## ABSTRACT

Using the theoretical formalism of **P Tassin *et al*. [Nature Photonics, 6, 259 (2012)] and C M Soukoulis *et al*. [Science 330, 1633 (2010)],** we have theoretically studied the comparison of grapheme, superconductors and metals as conductors for meta-materials and plasmonics. We observed the following facts:

We observed from the analysis of figure- of merit that grapheme and high-$T_C$ superconductors are not viable alternatives for metals in meta-materials.

For Plasmonic systems, our analysis indicate that grapheme and high $T_C$-superconductors cannot outperform gold as a platform for surface Plasmon polaritons, because grapheme has a smaller propagation length-to wavelength ratio.

Since the recent advancement in meta-materials and plasmonics have promised a number of exciting applications particularly at terahertz and optical frequencies this work will be quite useful in this regards. As noble metals used in these photonic structures are not good conductors at high frequencies resulting in significant dissipative loss, these findings will be helpful.

**Keywords:** Graphene, High $T_C$- superconductors, meta-materials, Plasmonics, Terahertz and optical frequencies, Figure-of-merit, Dissipation factor, Kinetic inductance factor, Ratio of propagation length to SPP (Surface Plasmon Polariton wavelength.

## INTRODUCTION

Meta materials and plasmonics are two branches of the study of light in electromagnetic structures, have emerged as promising scientific fields. Meta materials are engineered materials that consist of sub wavelength electric circuits replacing atoms as the basic unit of interaction with electromagnetic radiation[1-3]. They can provide optical properties that go beyond those of natural materials, such as magnetism at terahertz and optical frequencies[4-6], negative index of refraction[7-9], density waves at the surface of metals[11,12], which may be used for intra chip signal transmission, bio-photonic sensing applications and solar cells, among others[13-15].

Although, meta-materials and plasmonic systems promise the harnessing of light in unprecedented ways, they are also plagued by dissipative losses. This is probably the most important challenge to their applicability in real-world devices. In meta-materials, this results in absorption coefficients of tens of decibels per wavelength in the optical domain[16]. In plasmonic systems, dissipative loss is reflected in limited propagation length of surface Plasmon polaritons (SPPs) on the surface of noble metals[17,18]. These losses originate in the large electric currents leading to significant dissipation in the form of Joule heating. The enhanced electromagnetic fields close to the metallic constituents lead to relaxation losses in the dielectric substrates on which the metallic elements are deposited. It is to be noticed that even if the loss tangent of the constituent materials is small, significant losses still occur because the loss channels are driven by large resonant fields. If one focuses on terahertz frequencies and higher, loss is dominated by dissipation in the conducting elements, even if noble metals with relatively good electrical properties (Ag and Au) are used. It has been proposed to reduce the loss problem by replacing noble metals by other material elements[19], e.g. graphene[20,21] or high temperature superconductors[22]. Both material systems are known to be good conductors, at least for direct currents, and merit further investigation for use in meta-materials or plasmonic systems.

In this paper, we have theoretically made a comparison of grapheme, superconductors and metals for meta-materials and plasmonics. The evaluation is performed for Ag metal at room temperature and high $T_C$ superconductor YBCO at 10K and 50K below critical temperature 80K. The evaluation is done with the help of theoretical formalism of P. Tassin *et al.*[23], C. M. Soukoulis *et al.*[2,16]. We observed that graphene and high $T_C$-superconductors are not suitable alternatives for metals in meta-materials. Similarly grapheme and high $T_C$-superconductors cannot replace gold for plasmonics. These findings are very useful in the design of photonic devices.

## MATHEMATICAL FORMULA USED IN THE STUDY

### Figure –of-merit for conductors in resonant meta-materials

The meta-materials one considers here consist of an array of sub-wavelength conducting elements. It is for this type of structure that an effective permittivity and permeability make sense[24,25]. This allows modeling each individual element as a quasi-static electrical circuit described by the RLC circuits. This is the most general case, as some reported phenomena in meta-materials require more intricate circuits[25], but it was proven that it can well capture the physics of the most popular elements, such as split rings and wire pairs[26].

The analysis starts with describing the electrical current flowing in the metallic circuit of each meta-atom. Then, one calculates the permeability of the meta-materials and the dissipated power by summing the Joule heat loss for each circuit[27]. Expressed in dimensionless quantities, one finds that the dissipated power as a fraction of the incident power can be written in the following form;

$\prod =$ dissipated power per unit cell/Incident power per unit cell

$$= 2\pi\left(\frac{a_k}{\lambda_0}\right)\frac{F\bar{\omega}^4\zeta}{[\bar{\omega}^2(1+\xi)-1]^2+(\bar{\omega}\zeta+\tau\bar{\omega}^5)^2} \qquad (1)$$

Here, $\bar{\omega} = \omega/\omega_0$ is the renormalized frequency

$\omega_0 = (LC)^{\frac{-1}{2}}$ is the resonance frequency of the quasi-static circuit

F is the filling factor of the metal in the unit cell

$\zeta = \mathrm{Re}(R)/\sqrt{L/C}$ is the dissipation factor

$\xi = -\mathrm{Im}(R)/(\bar{\omega}\sqrt{L/\mathrm{C}})$ is the kinetic inductance factor

$\tau$ is a parameter describing radiation loss

$a_k$ is the meta-material's unit cell size along the propagation direction

$\lambda_0$ is the free space wavelength

The physical significance of these parameters is the following:

The dissipated power fraction quantifying the dissipative loss depends on just four independent dimensionless parameters

(i) The filling factor F

(ii) The radiation loss parameter $\tau$

(iii) The dissipation factor, $\zeta$ (proportional to the real part of resistivity)

(iv) The kinetic inductance factor, $\xi$ (proportional to the imaginary part of resistivity)

The filling factor and the radiation loss parameter depend only on purely geometric variables such as the area of the circuit and the geometric inductance, but not on the material properties of the conductor. Thus, for certain geometry (split rings or fishnet) F and $\tau$ are fixed. This means that one can limit this study to know as to how the dissipated power depends on $\zeta$ and $\xi$, the only two parameters that depend on the specific conducting material used.

The comparative study of conducting materials for resonant meta-materials in this work is based on the fact that the dissipated loss in normalized units can be written as a function of two material-dependent parameters-the dissipation factor and the kinetic inductance factor –as expressed in equation (1). This equation is obtained from a quasi-static analysis assuming the conductive elements of the meta-material to be smaller than the free-space wavelength of the incident radiation. Special attention is paid to the radiation resistance, since its neglect would lead to a circuit model where the dissipated power could become larger than the incident power. The radiation resistance term is obtained from a mean-field expansion of the magnetic fields generated by the circuit current. This is again justified by the sub-wavelength dimension of the circuit.

Now, one can exemplified the classification procedure for conducting materials using a particular meta-material constituent—the sub-wire pair. The dimension of the sub-wire pair is the following:

$l=2.19a_k$, $W=0.47a_k$, $t=0.5a_k$, $t_m=0.25a_k$ ($t_m$ is not relevant for two-dimensional conductors such as graphehe) $a_E=2.97a_k$ and $a_H=2.19a_k$. The relative permittivity of the substrate $\varepsilon_r=2.14$

One uses the simple expressions for the parallel-plate capacitor and for the solenoid inductance, they were shown to provide an adequate description for the slab-wire pair[28]

$$C=\varepsilon_0\varepsilon_r\frac{wl}{t},\ L=\mu_0\frac{lt}{a_H},\ \mathrm{R}=\frac{\rho}{t_m}\frac{2l}{w} \tag{2}$$

The area enclosed by the circuit is

$$A=lt \tag{3}$$

This is sufficient to calculate the geometry-dependent term of the dissipation and kinetic inductance factor

$$\zeta=\frac{\mathrm{Re}(\rho)}{t_m}\sqrt{\frac{\varepsilon_0}{\mu_0}}\sqrt{\varepsilon_r}\,\frac{2l\sqrt{a_H}}{t\sqrt{w}} \tag{4}$$

$$\xi=\frac{\mathrm{Im}(\rho)}{t_m}\frac{1}{\varpi}\sqrt{\frac{\varepsilon_0}{\mu_0}}\sqrt{\varepsilon_r}\,\frac{2l\sqrt{a_H}}{t\sqrt{w}} \tag{5}$$

The filling factor F and the radiation loss parameter $\tau$ can also be calculated

$$F=\mu_0A^2N/L=\frac{lt}{a_ka_E}=0.37 \tag{6}$$

$$\tau=\frac{1}{6\pi}\frac{\sqrt{\frac{\mu_0}{\varepsilon_0}}}{\sqrt{\frac{L}{C}}}\frac{\omega^4{}_0A^2}{c^4}=\frac{1}{6\pi}\frac{1}{\varepsilon^{\frac{3}{2}}{}_r}\frac{a^{\frac{5}{2}}{}_Ht}{l^2w^{\frac{3}{2}}}=0.039 \tag{7}$$

The calculation of the dissipation factor and the kinetic inductance factor for a slab-wire pair made of grapheme needs special consideration due to the two-dimensional nature of the current transport. The geometry-dependent terms in $\zeta$ and $\xi$ are calculated. The resistivity is obtained from experimental data of Li etal.[29]. The real part of the measured surface conductivity of grapheme equals to very good approximation $\sigma_0=\pi e^2/2h$=6.08x10$^{-5}$ S/m.

The imaginary part is more than 10 times smaller, and, as a consequence, there is a significant uncertainty in its measured value. One has fitted two Drude functions to the experimental data (i) the first provides a lower bound to the measured imaginary part of the conductivity (ii) the other provides a upper bound.

$$\mathrm{Re}(\rho) = \frac{\mathrm{Re}(\sigma)}{\mathrm{Re}(\sigma)^2 + \mathrm{Im}(\sigma)^2} \approx \frac{1}{\mathrm{Re}(\sigma)} \tag{8}$$

The properties of a surface Plasmon polariton $\exp[i(\beta z - \omega t]$ propagating in the z-direction on graphene

$$\beta = \frac{\omega}{c}\sqrt{1-(\frac{2}{\eta_0\sigma_H})^2} \tag{9}$$

Where $\eta_0$ is the characteristic impedance of free space. The SSP wavelength is obtained from $\lambda_{SPP} = 2\pi/[\mathrm{Re}(\beta)$, the propagation length by $\frac{1}{[\mathrm{Im}(\beta)]}$ and the lateral decay length by $= 1/\mathrm{Re}[\sqrt{\beta^2 - (\frac{\omega}{c})^2}]\cdot$

## DISCUSSION OF RESULTS

Using the theoretical formalism of P Tassin *et al.*[23] and Soukoulis *et al.*[3,16], we have performed a comparative study of grapheme, Superconductors and metals as conductors for meta-materials and Plasmonics. Recently, advancements in meta-materials and plasmonics have earned a number of exciting applications, in particular at terahertz and optical frequencies. Unfortunately, the noble metals used in these photonic structures are not particularly good conductors at high frequencies, resulting in significant dissipative loss. Here, we have addressed the question of what is a good conductor for meta-materials and plasmonics. **In table T1,** we have shown the evaluated result of dissipated power as a function of dissipation factor $\zeta$ at constant permeability. We have taken permeability $\mu$ =0, $\mu$ =-0.5, $\mu$ =-1.0, $\mu$ =-2.0. Our theoretically obtained results show that dissipative loss at constant permeability increase as function of dissipation factor**. In table T2,** we have shown the evaluated result of ratio of dissipated to incident power at resonance in meta-material with F=0.37 and $\tau$ =0.039 calculated for the slab-wire pair as a function of kinetic inductance factor $\xi$. The dissipated power is calculated at the operating frequency when $\mu(\omega) = -1$. Our evaluated results show that the dissipated power increase with kinetic inductance factor for small values and then it becomes flat and after that it decrease. **In table T3,** we have shown the evaluated result of comparison between the loss factors of charge neutral grapheme and gold. Here, the dissipation factor $\xi$ has been evaluated as a function of lattice constant ($\mu$ m). We observed that in case of gold, dissipation factor decrease with lattice constant but in the case of graphene it increase with lattice constant. **In table T4,** we have given the evaluated results of comparison between graphene and gold for kinetic inductance factor $\xi$ as a function of lattice constant. In this case, we observe that kinetic inductance factor decrease as function of lattice constant for both gold and graphene. **In table T5**, we have made a comparison of the plasmonic properties of grapheme and gold. The results for gold are for a 30-nm-thick film at room temperature. The results for graphene are for strongly biased graphene calculated from experimental data[30]. In theoretical calculation, we have incorporated electron-electron interactions from the conductivity of graphene. In fact, we have evaluated the ratio of propagation length to SPP wavelength as a function of frequency (THz). Our theoretically obtained results show that the ratio decreases with frequency. **In table T6,** we have presented an evaluated result of comparison of high $T_C$-superconductor YBCO at 10K and 50K below critical temperature 80K along with Ag at room temperature. Here, Re[Resistivity][S/m] has been evaluated as a function of frequency. The real part of the resistivity measure the dissipative loss. Our theoretically obtained results show that for Ag at room temperature dissipative loss is very small and is almost constant with frequency. On the other hand our results indicate that for high $T_C$ superconductor YBCO at 10K below critical temperature dissipative loss increase with frequency. The loss is higher at 50K than at 10K. **In table T7,** we have made companion of high $T_C$ superconductor YBCO at 10K and 50K below the critical temperature 8K along with Ag at room temperature by evaluating Im [Resistivity][S/m] as a function of frequency (THz). The imaginary part of resistivity measure the kinetic inductance. Our theoretically obtained results show that in this case the kinetic inductance increase with frequency for all the three cases. However, the kinetic inductance is low for Ag metal and for YBCO at 10K and 50K they are equal. Our theoretically obtained results are in good agreement with other theoretical workers[32,33.] There is some recent calculation[34-40] which also reveals the similar behavior.

**Table T1: An evaluated results of dissipated power as a function of dissipation factor $\zeta$ in a meta-materials With F= 0.37 and $\tau$ =0.039 quantities calculated for the slab-wire pair. The dissipated power is calculated at constant permeability $\mu$ =0, -0.5, -1 and -2 respectively.**

| Dissipation factor $\zeta$ | < -- Dissipative loss at constant permeability-----→ | | | |
|---|---|---|---|---|
| | $\mu$ =0 | $\mu$ =-0.5 | $\mu$ =-1.0 | $\mu$ =-2 |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.01 | 0.002 | 0.004 | 0.005 | 0.007 |
| 0.02 | 0.004 | 0.006 | 0.006 | 0.010 |
| 0.03 | 0.006 | 0.008 | 0.008 | 0.014 |
| 0.04 | 0.008 | 0.010 | 0.010 | 0.017 |
| 0.05 | 0.010 | 0.014 | 0.015 | 0.020 |
| 0.06 | 0.012 | 0.016 | 0.018 | 0.024 |
| 0.07 | 0.014 | 0.018 | 0.020 | 0.032 |
| 0.08 | 0.016 | 0.020 | 0.024 | 0.035 |
| 0.09 | 0.018 | 0.024 | 0.026 | 0.040 |
| 0.10 | 0.020 | 0.030 | 0.032 | 0.050 |
| 0.12 | 0.021 | 0.040 | 0.045 | 0.064 |
| 0.14 | 0.022 | 0.050 | 0.061 | 0.072 |
| 0.15 | 0.024 | 0.060 | 0.070 | 0.080 |

**Table T2: An evaluated results of dissipated power at resonance as a function of dissipation factor $\zeta$ for meta-material in the form of slab-wire pair**

| Dissipation factor $\zeta$ | Dissipated power at resonance |
|---|---|
| 0.00 | 0.000 |
| 0.01 | 0.37 |
| 0.02 | 0.46 |
| 0.03 | 0.57 |
| 0.04 | 0.65 |
| 0.045 | 0.72 |
| 0.05 | 0.80 |
| 0.055 | 0.84 |
| 0.060 | 0.86 |
| 0.065 | 0.85 |
| 0.070 | 0.84 |
| 0.075 | 0.82 |
| 0.080 | 0.80 |
| 0.085 | 0.75 |
| 0.090 | 0.73 |
| 0.10 | 0.70 |

**Table T3: An evaluated results of comparisons between the loss factors of charge neutral graphene and gold, here, the dissipation factor $\zeta$ is evaluated as a function of lattice constant ( $\mu m$ )**

| Lattice constant ( $\mu m$ ) | < ---- Dissipation factor $\zeta$ --------→ | |
|---|---|---|
| | Gold | Graphende |
| 0.10 | 0.50 | 110.2 |
| 0.15 | 0.20 | 111.6 |
| 0.20 | 0.10 | 112.8 |
| 0.30 | 0.06 | 113.7 |
| 0.40 | 0.07 | 114.6 |
| 0.50 | 0.05 | 115.5 |
| 0.60 | 0.006 | 116.9 |
| 0.70 | 0.005 | 117.7 |
| 0.80 | 0.004 | 118.8 |
| 0.90 | 0.003 | 119.0 |
| 1.00 | 0.002 | 120.5 |
| 2.00 | 0.001 | 121.3 |
| 3.00 | 0.005 | 122.3 |
| 4.0 | 0.004 | 123.9 |
| 5.0 | 0.003 | 124.4 |
| 6.0 | 0.002 | 125.6 |
| 10.0 | 0,0008 | 126.8 |

**Table T4 : An evaluated results of comparisons between the loss factors of charge neutral graphene and gold, here, the dissipation factor $\zeta$ is evaluated as a function of lattice constant ( $\mu m$ )**

| Lattice constant ( $\mu m$ ) | < ---- Dissipation factor $\xi$ --------→ | |
|---|---|---|
| | Gold | Graphende |
| 0.10 | 1.254 | 112.3 |
| 0.15 | 1.203 | 110.0 |
| 0.20 | 1.187 | 104.9 |
| 0.30 | 1.102 | 100.7 |
| 0.40 | 0.958 | 98.4 |
| 0.50 | 0.732 | 75.2 |
| 0.60 | 0.547 | 67.4 |
| 0.70 | 0.087 | 50.2 |
| 0.80 | 0.065 | 42.4 |
| 0.90 | 0.054 | 36.5 |
| 1.00 | 0.042 | 34.3 |
| 2.00 | 0.010 | 30.0 |
| 3.00 | 0.008 | 27.6 |
| 4.0 | 0.007 | 20.8 |
| 5.0 | 0.006 | 18.2 |
| 6.0 | 0.005 | 15.4 |
| 10.0 | 0.003 | 10.6 |

**Table T5 : An evaluated result of comparison of Plasmonic properties of grapheme and Gold, here, the ratio of propagation length to SSP wavelength is evaluated as a function of frequency (THz)**

| Frequency (THz) | Propagation length/SSP wavelength | |
|---|---|---|
| | Gold | Graphene |
| 10 | $2x10^{4}$ | $20x10^{0}$ |
| 20 | $1x10^{4}$ | $18x10^{0}$ |
| 30 | $9x10^{2}$ | $16x10^{0}$ |
| 40 | $8x10^{2}$ | $15x10^{0}$ |
| 50 | $7x10^{2}$ | $14x10^{0}$ |
| 100 | $6x10^{2}$ | $17x10^{0}$ |
| 200 | $5x10^{2}$ | $20x10^{0}$ |
| 400 | $4x10^{2}$ | $13x10^{0}$ |
| 500 | $3x10^{2}$ | $12x10^{0}$ |
| 600 | $2x10^{2}$ | $10x10^{0}$ |
| 800 | $1x10^{2}$ | $8x10^{-2}$ |
| 800 | $9x10^{1}$ | $6x10^{-2}$ |
| 1000 | $8x10^{1}$ | $5x10^{-2}$ |
| 1200 | $7x10^{1}$ | $4x10^{-2}$ |
| 1400 | $6x10^{1}$ | $3x10^{-2}$ |
| 1500 | $5x10^{1}$ | $2x10^{-2}$ |

**Table T6 : An evaluated result of comparison of High-$T_C$ superconductor YBCO at 10K and 50K below critical temperature 80K with Ag at room temperature, here, Re[Resistivity][S/m] has been evaluated as a function of frequency (THz). Real part of resistivity is a measure of the dissipative loss.**

| Frequency (THz) | < ----- Re[Resistivity][S/m]-------------→ | | |
|---|---|---|---|
| | Ag(Room Temp) | YBCO (10K) | YBCO (50K) |
| 0.5 | $5x10^{-8}$ | $6x10^{-8}$ | $7x10^{-7}$ |
| 0.7 | $7x10^{-8}$ | $7x10^{-8}$ | $8x10^{-7}$ |
| 1.0 | $9x10^{-8}$ | $8x10^{-8}$ | $9x10^{-7}$ |
| 1.2 | $10x10^{-8}$ | $9x10^{-8}$ | $8x10^{-6}$ |
| 1.4 | $11x10^{-8}$ | $9x10^{-7}$ | $6x10^{-6}$ |
| 1.6 | $12x10^{-8}$ | $8x10^{-7}$ | $5x10^{-6}$ |
| 1.8 | $14x10^{-8}$ | $7x10^{-7}$ | $4x10^{-6}$ |
| 2.0 | $16x10^{-8}$ | $6x10^{-7}$ | $3x10^{-6}$ |
| 2.2 | $18x10^{-8}$ | $5x10^{-7}$ | $2x10^{-6}$ |
| 2.4 | $22x10^{-8}$ | $4x10^{-7}$ | $6x10^{-7}$ |
| 2.5 | $24x10^{-8}$ | $3x10^{-7}$ | $5x10^{-7}$ |
| 2.6 | $26x10^{-8}$ | $9x10^{-6}$ | $4x10^{-7}$ |
| 2.7 | $30x10^{-8}$ | $8x10^{-6}$ | $3x10^{-7}$ |
| 2.8 | $32x10^{-8}$ | $7x10^{-6}$ | $2x10^{-7}$ |
| 3.0 | $34x10^{-8}$ | $6x10^{-6}$ | $1x10^{-7}$ |

**Table T7 : An evaluated result of comparison of the high $T_C$-superconductor YBCO at 10K and 50K with Ag at room temperature, here, Im [Resistivity][S/m] is evaluated as a function of frequency (THz). Imaginary part of the resistivity measures the kinetic inductance.**

| Frequency (THz) | < ------- Im [Resistivity][S/m]------------→ | | |
|---|---|---|---|
| | Ag (room temp.) | YBCO (10K) | YBCO (50K) |
| 0.5 | $2x10^{-9}$ | $8x10^{-7}$ | $6x10^{-7}$ |
| 0.7 | 3x10-9 | $9x10^{-7}$ | $7x10^{-7}$ |
| 1.0 | $4x10^{-9}$ | $2x10^{-6}$ | $8x10^{7}$ |
| 1.2 | $5x10^{-9}$ | $4x10^{-6}$ | $9x10^{-7}$ |
| 1.4 | $6x10^{-9}$ | $5x10^{-6}$ | $4x10^{-6}$ |
| 1.6 | $7x10^{-9}$ | $6x10^{-6}$ | $5x10^{-6}$ |
| 1.8 | $8x10^{-9}$ | $7x10^{-6}$ | $6x10^{-6}$ |
| 2.0 | $2x10^{-8}$ | $3x10^{-6}$ | $7x10^{-6}$ |
| 2.2 | $3x10^{-8}$ | $4x10^{-6}$ | $8x10^{-6}$ |
| 2.4 | $4x10^{-8}$ | $5x10^{-6}$ | $9x10^{-6}$ |
| 2.6 | $5x10^{-8}$ | $6x10^{-6}$ | $4x10^{-6}$ |
| 2.7 | $6x10^{-8}$ | $7x10^{-6}$ | $5x10^{-6}$ |
| 2.8 | $7x10^{-8}$ | $8x10^{-6}$ | $6x10^{-6}$ |
| 3.0 | $8x10^{-8}$ | $9x10^{-6}$ | $7x10^{-6}$ |

## CONCLUSION

From the above theoretical investigations and analysis, we have come across the following conclusions

(1) We observed from the analysis of figure- of merit that grapheme and high-$T_C$ superconductors are not viable alternatives for metals in meta-materials.

(2) For Plasmonic systems, our analysis indicate that grapheme and high $T_C$- superconductors cannot outperform gold as a platform for surface Plasmon polaritons, because grapheme has a smaller propagation length-to wavelength ratio.

(3) Since the recent advancement in meta-materials and plasmonics have promised a number of exciting applications particularly at terahertz and optical frequencies this work will be quite useful in this regards. As noble metals used in these photonic structures are not good conductors at high frequencies resulting in significant dissipative loss, these findings will be helpful.

## REFERENCES

1. D R Smith *et al.*, 'Meta-materials and negative refractive index" *Science*, 305, 788 (2004).
2. V M Shalaev, "Optical negative-index meta-materials". *Nature Photon*, 1, 41 (2006).
3. C M Soukoulis *et al*., "Optical meta-materials-more bulky and less lossy" *Science* 330, 1633 (2010).
4. T Yen *et al*., Terahertz magnetic response from artificial materials, *Science*, 303, 1494 (2004).
5. S Linden *et al*., "Magnetic response of meta-materials at 100terahertz" S*cience* 306, 1351 (2004).
6. C Enkrich *et al*., 'Magnetic meta-materials in telecommunication and visible frequencies' *Phys. Rev. Lett. (PRL)* 95, 203901 (2005).
7. R A Shelby *et al*., 'Experimental verification of negative index of refraction" *Science* 292, 77 (2001).
8. S Zhang *et al*. Experimental demonstration for negative index mata-materials, *Phys. Rev. Lett. (PRL)* 95, 137404 (2005).
9. V M Shalaelv *et al.*, Negative index of refraction in optical meta-materials, *Opt. Lett.* 30, 3356 (2005).
10. E Plum *et al*., Meta-material with negative index due to chirality, *Phys. Rev B*79, 035407 (2009).
11. E N Economou, Surface Plasmon in thin films, *Phys. Rev*. 182, 539 (1969).
12. A D Boardman, Electromagnetic surface modes (Wiley, New York, 1982).
13. S A Maier and H A Atwater, Plasmonics localization and guiding electromagnetic energy in metal/dielectric structures, *J. Appl. Phys*, 98, 011101 (2003).
14. D K Gramotnev *et al*., Plasmonics beyond te diffraction limit' *Nature Photon*. 4, 83 (2010).
15. K R Catchpole *et al*., Plasmonic solar cells, *Opt. Express* 16, 21793 (2008).
16. C M Soukoulis *et al*., The science of negative index materials' *J. Phys. Cond. Mater*, 20, 304217 (2008).
17. S I Bozhevolnyi *et al*., Plasmon polariton guiding by subwavelength metal grooves, *Phys. Rev. Lett. (PRL)* 95, 046802 (2005).
18. A Kolomenski *et al*., Propagation length of surface plasmon in metal film with roughness, *Appl. Opt*. 48, 5683 (2009).
19. A Boltasseva *et al*., Low loss plasmonic meta-materials, *Science*, 331, 290 (2011).
20. A Vakil *et al*., Transformation optics using graphene, *Science*, 332, 1291 (2011).

21. F H L Koppens *et al*., Graphene Plasmonics: A platform for strong light-matter interactions, *Nano Lett.* 11,3370 (2011).
22. H T Chen *et al*., Tuning the resonance in high temperature superconducting terahertz meta-meta-materials, *Phys. Rev. Lett. (PRL)* 105, 247402 (2010).
23. J Pendry *et al*., Magnetism from conductors and enhanced non-linear phenomenon, *IEEE Trans. Microwave theory Tech*., 47, 2075 (1999).
24. M Gorunov *et al*., Effective magnetic properties of composite materials withcicular conductive elements. *Eur. Phys. J., B*28, 263 (2002).
25. N Engheta, Circuits with light at nanoscales: optical nanocircuits inspired by meta-materials, *Science* 317, 1698 (2007).
26. T Koschny *et al*., Effective medium theory of left handed materials*, Phys. Rev. Lett. (PRL)* 93, 107402 (2004).
27. S Zhang *et al*., Plasma induced transparency in meta-materials, *Phys. Rev. Lett. (PRL)* 101, 047401 (2008).
28. N Papasimakis *et al*., Meta-material analog of electromagnetically induced transoarency, *Phys. Rev. Lett. (PRL)* 101, 253903 (2008).
29. Z Q Li *et al*., 'Dirac charge dynamics in grapheme in infrared spectroscopy' *Nature Phys*. 4, 532 (2008).
30. P Tassin *et al*., Low loss meta-materials based on classical electromagnetically induced transparency, *Phys. Rev. Lett. (PRL)* 102, 053901 (2009).
31. N Liu *et al*., Plasmonic analogue of electromagnetically induced spectroscopy at the Drude damping limit, *Nature mater,* 8, 758 (2009).
32. R S Penciu *et al*., Magnetic response of nano scale left-handed meta-materials, *Phys. Rev. B*81, 235111 (2010)
33. P Bonaccorso *et al*., Graphene photonics and optoelectronics, *Nature Photon*, 4, 611 (2010).
34. J Horng *et al*., Drude conductivity of Dirac fermions in grapheme, *Phys. Rev. B*83, 165113 (2011).
35. A. Politanni *et al*., Collective electronic excitation in thin Ag films, *Plasmonic*, 8, 1683 (2013).
36. X. H. Yao *et al*., Effective non linear generation of THz plasmonics in grapheme and topological insulators*, Phys. Rev. Lett. (PRL)* 112, 055502 (2014).
37. Y. L. Yan *et al*., A simple nano scale plasmonic waveguide. *Progree in electromagnetic research Lett*., 51, 39 (2015).
38. A. M. Brown *et al*., Nonradiative Plasmon decay and hot carrier dynamics, *ACS Nano*, 10, 957 (2016).
39. S Zhao *et al*., Two-dimensional metallic $NbS_2$ growth ---transport properties in grapheme, *2D Mater*, 3, 25927 (2016).
40. M N Gjerding, Band structure engineered layer metal for low loss plasmonic, *Nat Commun*. 8, 15132 (2017).