Temperature-dependent effect of modulation in graphene-supported metamaterials

Yevhenii M Morozov¹,²,∗, Anatoliy S Lapchuk², Iryna S Prottsak³, Andriy A Kryuchyn² and Ivan P Nevirkovets⁴

¹ Biosensor Technologies, AIT-Austrian Institute of Technology, 3430 Tulln, Austria
² Department of Optical Engineering, Institute for Information Recording of NAS of Ukraine, 03113 Kyiv, Ukraine
³ Department of Biomedical Problems of Surface, Chuiko Institute of Surface Chemistry of NAS of Ukraine, 03164 Kyiv, Ukraine
⁴ Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, United States of America

∗ Author to whom any correspondence should be addressed.
E-mail: Yevhenii.Morozov@ait.ac.at

Keywords: graphene, metamaterials, electro-optical modulators/switchers, modulation depth, temperature dependence, theoretical analysis

Abstract

We report on a novel effect of temperature-dependent modulation in graphene-supported metamaterials. The effect was observed during the theoretical analysis of a model graphene-supported electro-optical modulator having silicon dioxide (SiO₂) or hafnium dioxide (HfO₂) as a buffer dielectric layer. Comparative analysis of the two materials showed that they provide approximately the same maximum values for transmission and reflection modulation depths. However, in the case of a HfO₂ buffer layer, a lower chemical potential of the graphene is required to achieve the maximum value. Moreover, theoretical calculations revealed that a lower gate voltage (up to 6.4 times) is required to be applied in the case of a HfO₂ layer to achieve the same graphene chemical potential. The graphene layer was found to possess high absorption (due to the additional resonance excitation) for some values of chemical potential and this effect is extremely temperature dependent. The discovered modulation effect was demonstrated to further increase the transmission modulation depth for the simple model structure up to 2.7 times (from 18.4% to 50.1%), while for the reflection modulation depth, this enhancement was equal to 2.2 times (from 24.4% to 52.8%). The novel modulation effect could easily be adopted and applied over a wide range of metadevices which would serve as a quick booster for the development of related research areas.

1. Introduction

Artificial composite materials engineered to manifest exotic electromagnetic (EM) phenomena—namely, metamaterials (MMs)—has found a wide application in optical modulators, switchers, sensors, and other devices by providing additional degrees of freedom in light manipulation [1–6]. Moreover, EM response of an MM can be actively tuned by an external stimulus such as optical, thermal, electric, or magnetic. Additionally, inclusion of a semiconductor layer into the MM can further increase its tunability by means of active control of its capacitance or refractive index (e.g., by varying the applied external voltage) [7, 8].

Due to unique electrical, optical, thermal, mechanical, and, in some reported cases, biocompatible properties, graphene and its derived forms have been intensively explored for a wide range of applications [9–14]. Moreover, graphene-supported devices have recently been considered as a subject for combining with a relatively well-established research field such as plasmonic biosensors, which also revealed new intriguing features [15]. Additionally, because the graphene layer itself can support different kind of plasmonic resonances, graphene plasmonics has emerged recently as a promising field to further advance the applications [16–22].
In the present work, we aimed to further increase the actively controlled modulation depth of graphene-based optical modulators/switchers and to simultaneously reduce the applied voltage $V_g$ required to achieve maximum modulation values. Reducing $V_g$ is especially important for development of an optical input/output interface between Josephson junction circuits operating at cryogenic temperatures \cite{23, 24} and room temperature electronics. Electrical to optical (EO) signal conversion and transmission from the cryogenic to the room temperature environment is advantageous because EO modulators are voltage controlled, and can be made rather small; in addition, the control voltage can be reduced, first, by proper choice of dielectrics with high permittivity, and second, by using MM design. Since the maximum driving voltage for the device considered here is expected to be on the order of 0.1 V, the critical voltage of the Josephson junction used in typical single-flux quantum (SFQ) circuits ($\sim$1 mV) is too low to produce electrooptical modulation. Therefore one needs a device interfacing a low-voltage SFQ output with a higher voltage EO device input. Such a device, in its preliminary, unoptimized embodiment, is proposed in reference \cite{25}.

Here we consider MM devices involving two materials—silicon dioxide (SiO$_2$) and hafnium dioxide (HfO$_2$)—as a buffer dielectric layer in a relatively simple model structure (see 3D view and schematics with notations of the structure in figure 1) \cite{17}. As a ‘side effect’ result, it was found that the graphene layer possesses high absorption for some values of chemical potential and this effect is strongly temperature dependent. The newly discovered effect was also investigated in detail by numerical simulation means and the obtained results were discussed and interpreted accordingly.

![Figure 1. (a) 3D view and (b), (c) schematics with notations of the model structure under consideration.](image-url)
2. Details of the theoretical analysis

The energy–momentum relationship for electrons in graphene is linear over a wide range of energies, therefore the electrons can be considered as massless relativistic particles (so-called Dirac fermions). Low-energy conductivity ($< 3$ eV) of graphene $\sigma_g$ consists of intraband and interband contributions and can be derived from the Kubo formula [17, 26] while ignoring the Hall effect as follows:

$$\sigma_g(\omega, \mu_c, \Gamma, T) = -\frac{i e^2}{\pi \hbar^2} \times \left[ \frac{1}{(\omega + i 2 \Gamma)^2} \int_0^\infty \varepsilon \left( \frac{\partial f_\varepsilon(-\varepsilon)}{\partial \varepsilon} - \frac{\partial f_\varepsilon(\varepsilon)}{\partial \varepsilon} \right) d\varepsilon - \int_0^\infty \frac{f_\varepsilon(-\varepsilon) - f_\varepsilon(\varepsilon)}{\left(\omega + i 2 \Gamma\right)^2 - 4 \left(\varepsilon / \hbar \right)^2} \right], \quad (1)$$

where $i$ is the imaginary unit, $e$ is the electron charge, $\omega$ is radian frequency, $\Gamma$ is scattering rate, $\hbar$ is reduced Planck’s constant, $\varepsilon$ is energy, and $f_\varepsilon(\varepsilon)$ is the Fermi–Dirac distribution. Chemical potential of graphene $\mu_c$ is determined by the carrier density $n$ as

$$n = -\frac{2}{\pi v_F^2 \hbar^2} \int_0^\infty \varepsilon \left[ f_\varepsilon(\varepsilon) - f_\varepsilon(\varepsilon + 2 \mu_c) \right] d\varepsilon, \quad (2)$$

where $v_F$ is the Fermi velocity. It is thus clear from the equation (2) that carrier density $n$ can be tuned by varying the chemical potential $\mu_c$ which, in turn, can be actively tuned by varying the applied voltage $V_g$ (see figure 1 and equation (4)). Given the graphene surface conductivity $\sigma_g$, its dielectric constant $\varepsilon_g$ can be deduced as

$$\varepsilon_g = 1 + \frac{\sigma_g}{\omega \varepsilon_0 \Delta}, \quad (3)$$

where $\varepsilon_0$ is the permittivity of free space and $\Delta$ is the graphene layer thickness. Electron relaxation time in graphene, $\tau$, was set to 0.1 ps for all values of the temperature $T$.

Modulation depth $X_m$ ($X =$ Transmission, Reflection, or Absorption) was calculated as $X_m = (X_{\text{max}} - X_{\text{min}}) / X_{\text{max}}$ where $X_{\text{min}}$ and $X_{\text{max}}$ correspond to the minimum and maximum values, respectively, at a certain frequency point. Chemical potential values $\mu_c$ were varied in a range from 0.1 to 0.7 eV. Numerical simulations were performed in the frequency domain (finite element method) with unit-cell boundary conditions in the $x$–$y$ plane and Floquet boundaries were applied in planes at minimum ($z_{\text{min}}$) and maximum ($z_{\text{max}}$) values of $z$ coordinate. The structure was excited with $y$-polarized TEM$_{00}$ mode from $z_{\text{max}}$ plane which then propagated along the $z$ direction to $z_{\text{min}}$ plane. Due to the absolute symmetry of the considered geometry according to the $x$–$z$ and $y$–$z$ planes, excitation with $x$-polarized TEM$_{00}$ mode will give the identical results. The unit cells of MMMs are made of Ag with a thickness of 100 nm. The following parameters were used for the initial model: unit cell periods $p_x = p_y = 900$ nm; the length $h$ and width $w$ of the cross structure are 450 and 90 nm, respectively; thickness of the SiO$_2$ or HfO$_2$ buffer dielectric layer $d$ is 10 nm; the substrate is made of polyimide. A results convergence analysis was carried out before the main investigation (see figure S1 (https://stacks.iop.org/NJP/24/043006/mmedia) in supporting information).
3. Results and discussion

Table 1 shows values for $T_m$, $R_m$, and $A_m$ for different thickness $d$ of SiO$_2$ or HfO$_2$ layers. Transmission, reflection, and absorption values were taken at the frequency points corresponding to the extremum for curves at $\mu_c = 0.7$ eV. More detailed data on the temperature dependence of $T_m$, $R_m$, and $A_m$ in the range of 135.25 to 333.15 K in the case of SiO$_2$ and HfO$_2$ buffer layers are provided in figure S2.

From results presented in table 1 and figure S2, it is clear that temperature change in the considered range does not lead to noticeable change of the modulation depth. However, the modulator with a HfO$_2$ layer is more temperature stable than that with a SiO$_2$ layer in the temperature range from 153.15 to 273.15 K (standard deviations are at least two times lower for HfO$_2$ layer). Besides, decreasing the thickness $d$ of both SiO$_2$ and HfO$_2$ layers from 10 to 5 nm leads to increasing the $T_m$, $R_m$, and $A_m$, while increasing the thickness $d$ from 10 to 20 nm leads to decreasing the $T_m$, $R_m$, and $A_m$ (see table 1). However, it should be noted that the maximum modulation depths $T_m$, $R_m$, and $A_m$ shown in table 1 in case of a HfO$_2$ layer can be already achieved with the chemical potential $\mu_c$ of 0.5 eV while it has to be increased to 0.6 eV in the case of a SiO$_2$ layer (see figure 2).
It is also worth noting that despite insignificant modulation depth differences obtained for SiO2 and HfO2 layers, the applied voltage $V_g$ which is required to achieve the same chemical potential $\mu_c$ (and the modulation depths corresponding to this chemical potential value) will not be the same in both cases. This is due to the fact that the static dielectric constant $\varepsilon_s$ of SiO2 and HfO2 differs significantly [27]—3.9 for SiO2 and 25 for HfO2. To simplify the assessment of the required applied voltage $V_g$, the following equation can be considered [28]:

$$V_g = \frac{d \cdot e}{\varepsilon_s \varepsilon_0 \hbar^2 v_F^2} \int_0^\infty \varepsilon \left[ f_d(\varepsilon) - f_d(\varepsilon + 2\mu_c) \right] d\varepsilon,$$

where $d$ is the thickness of the buffer dielectric layer, $e$ is the electron charge, $\varepsilon_s$ is the static dielectric constant of the dielectric layer, $\varepsilon_0$ is the vacuum permittivity, $\hbar$ is the reduced Planck’s constant, $v_F$ is the Fermi velocity, $\varepsilon$ is energy, and $f_d(\varepsilon)$ is the Fermi–Dirac distribution. At room temperature and below it: $kT/\mu_c \ll 1$ (where $k$ is the Boltzmann constant), and therefore temperature changes in the range considered in the paper cannot significantly affect the Fermi velocity. As both considered structures are physically and geometrically identical (with the only exception being the buffer dielectric layer material), equation (4) can be rewritten as

$$V_g = \frac{C(\mu_c)}{\varepsilon_s},$$

where $C(\mu_c)$ is a function that is dependent on $\mu_c$ and takes the same value for both structures with the same specific value of $\mu_c$. Therefore, the voltage $V_g$ required to achieve a certain value of chemical potential $\mu_c$ (let say $\mu_c = 0.5 \text{ eV}$) depends only on the static dielectric constant $\varepsilon_s$ of the buffer layer. Then, for the SiO2 layer, one can write

$$V_{g\text{SiO2}} = \frac{C(\mu_c = 0.5)}{\varepsilon_s\text{SiO2}} (= 3.9),$$

and for the HfO2 layer

$$V_{g\text{HfO2}} = \frac{C(\mu_c = 0.5)}{\varepsilon_s\text{HfO2}} (= 25).$$

After dividing equation (6) by equation (7) one can obtain

$$\frac{V_{g\text{SiO2}}}{V_{g\text{HfO2}}} = \frac{\varepsilon_s\text{HfO2}}{\varepsilon_s\text{SiO2}} = \frac{25}{3.9} \approx 6.4,$$

i.e., to achieve the same chemical potential $\mu_c$ in the case of a SiO2 layer, one needs to apply a voltage 6.4 times higher than that for the HfO2 layer. In addition, taking into account the supercapacity effect shown for HfO2 in [20], in a real experiment this difference can be even bigger. However, it is worth of noting that dielectric permittivity of a material chosen for the buffer layer should not be very high due to the fact that this will lead to high remnant polarization, high hysteresis, and long retention times of the buffer layer [29] which, in turn, will lead to a slowdown in operation of the device.

Moreover, during the analysis, an interesting phenomenon was observed. In figure 3, dependence of the transmission, reflection, and absorption on frequency are shown for the modulator with a SiO2 layer of 10 nm for a temperature of 135.25 K (a), (b), (c) and 293.15 K (d), (e), (f).
The spectra shown in figure 3 are typical for a damped oscillating system, however for a temperature of 135.25 K and for $\mu_c = 0.5$ eV there are new local extrema at the frequency of 196.076 THz. At the same time, these additional local extrema are not so pronounced at a temperature of 293.15 K (see figures 3(d), (e) and (f)). In this way, it was established that with the temperature decreasing, an additional resonance occurs and becomes more pronounced.

Figure 4 shows the transmission spectra for the modulator with a SiO$_2$ layer of 10 nm for a temperature $T$ of 135.25 K and different values of the chemical potential $\mu_c$. From figure 4 it is obvious that for certain temperature value the resonance becomes more pronounced for a specific chemical potential range.

The same phenomenon was observed in the case of a HfO$_2$ layer of 10 nm (figure 5). However, in the case of a HfO$_2$ layer, additional features are not so pronounced as for the SiO$_2$ one. For a temperature of 135.25 K and $\mu_c = 0.5$ eV, additional local extrema are observed at a frequency of 196.016 THz.

Results presented in figures 3–5 lead to important consequences. One of them is that, by actively tuning the graphene chemical potential $\mu_c$ under the specific temperature $T$, it is possible to achieve much higher modulation depths $T_m$, $R_m$, and $A_m$ in comparison with the operation regime which is outside the range of this additional temperature-dependent effect. Specifically, consider (a) transmission, (b) reflection, and (c) absorption spectra (figure 6) of the metadevice having a SiO$_2$ buffer layer of 10 nm at $T = 135.25$ K. At
Figure 6. Dependence of (a) transmission, (b) reflection, and (c) absorption on frequency for the graphene-based model modulator with SiO$_2$ layer of 10 nm at the temperature $T = 135.25$ K.

$\mu_c = 0.489$ eV, the frequency of the additional resonance, $f = 191.573$ THz, coincides with the main resonance. In this case one can easily observe an increased absorption—from 0.399 at $\mu_c = 0.600$ eV to 0.455 at $\mu_c = 0.489$ eV (which is equal to an increased absorption modulation depth $A_m$ of 12.0%—compare with $A_m$ of 7.9% from table 1 for the usual operation regime). Transmission modulation depth $T_m$ is equal to 39.1% if considering switching between $\mu_c$ values of 0.100 and 0.489 eV; it is even higher (50.1%) if considering switching between $\mu_c$ values of 0.600 and 0.489 eV—this is a 2.7 times higher modulation depth $T_m$ than that which can be achieved in the case of switching in the usual operation regime (from 0.1 to 0.6 or 0.7 eV, see table 1). Finally, the reflection modulation depth $R_m$ is equal to 52.8% in the case of switching between 0.600 and 0.489 eV—which is a 2.2 times higher modulation depth $R_m$ than that which can be achieved in the case of switching in the usual operation regime (see table 1).

Figure 7 illustrates the dependence of (a) transmission, (b) reflection, and (c) absorption on the frequency for $\mu_c = 0.5$ eV for different temperatures in the case of a SiO$_2$ layer of 10 nm. The same behaviour of the modulator was qualitatively observed in the case of a HfO$_2$ buffer layer (see figure S3).

From figure 7 it is clear that these additional peaks in the spectra tend to (1) red-shift and (2) 'disappear' with increasing temperature. At the same time, the main peak tends to preserve its position.

Results presented in figures 3–7 can be interpreted in the form of two statements as follows:

(a) The main resonance is weakly dependent on the temperature $T$ and the graphene chemical potential $\mu_c$ and thus has to be referred to the plasmonic resonance in the gaps formed by cross structure (vertical or horizontal gap, depending on the excitation light polarization). This resonance is mainly determined by the geometrical and EM parameters of the cross structure and buffer dielectric layer. Frequency red-shifting of the main peak in the case of the HfO$_2$ layer which has a greater dielectric permittivity than that of the SiO$_2$ layer additionally confirms the first statement.

(b) Additional 'subresonance' is obviously related to a resonance excitation in the graphene layer due to its strong dependence on the temperature $T$ and the graphene chemical potential $\mu_c$. In general, a resonance excitation in the graphene layer should be characterized by a broader peak because...
plasmonic modes in graphene are usually characterized by a low $Q$-factor and, therefore, by a very high absorption \[30\]. Relatively narrow peaks in the present case can be only attributed to a strong dispersion of the graphene in the chemical potential range in which the resonance is most pronounced (see figure S4(a)). This fact also indirectly confirms the second statement.

Taking into account all the above, it seems practical to analyse the observed temperature-dependent behaviour of the graphene-supported MMs in more detail by both theoretical and experimental means in future research, which we believe will serve as a quick booster for the development of related research areas.

4. Conclusion

In summary, a temperature-dependent behaviour of a model graphene-supported MM device has been theoretically investigated in great detail. First of all, modulation depth values of the device have been
compared in the case of different buffer dielectric layer material—namely, silicone dioxide (SiO\(_2\)) and hafnium dioxide (HfO\(_2\)). It has been found that despite insignificant difference in the modulation depth for both layers, the maximum modulation depth for the HfO\(_2\) layer can be reached at lower graphene chemical potential \(\mu_c = 0.5\) eV (while it should be increased to 0.6 eV for the SiO\(_2\) layer). In addition, it has been analytically shown that a lower gate voltage \(V_g\) (up to 6.4 times) is required to be applied in the case of the HfO\(_2\) layer to achieve the same graphene chemical potential.

Moreover, it has been found and discussed in detail that the graphene layer possesses high absorption (due to the additional resonance excitation) for some values of chemical potential and this effect is strongly temperature dependent. For the simple model structure, the discovered modulation effect was demonstrated to further increase the transmission modulation depth up to 2.7 times (from 18.4% to 50.1%); at the same time, for reflection modulation, this enhancement was equal to 2.2 times—from 24.4% to 52.8%. Results presented here can be potentially useful and important for the design of any graphene-supported modulators, switches, sensors, or other devices.

Acknowledgments

This work was supported by the National Academy of Sciences of Ukraine (Grant 0119U001105). YMM acknowledges support from the Austrian Science Fund (FWF) through the Lise Meitner Programme (Grant M 2925). As well, YMM is grateful to Stefan Fossati for fruitful discussions of the obtained results. IPN was supported from the National Science Foundation—DMR (Grant 1905742). The authors acknowledge V Nevirkovets for proofreading the manuscript.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Yevhenii M Morozov https://orcid.org/0000-0001-9689-8641

References

[1] Chen H-T, Padilla W J, Zide J M O, Gossard A C, Taylor A J and Averitt R D 2006 Active terahertz metamaterial devices Nature 444 597–600
[2] Zheludev N I and Kivshar Y S 2012 From metamaterials to metadevices Nat. Mater. 11 917–24
[3] Zhong J, Xu X and Lin Y-S 2021 Tunable terahertz metamaterial with electromagnetically induced transparency characteristic for sensing application Nanomaterials 11 2175
[4] Vafapour Z, Dutta M and Strusciog M A 2021 Sensing, switching and modulating applications of a superconducting THz metamaterial IEEE Sensors J. 21 15187–95
[5] Wang J-N, Xiong B, Liu Y, Chen C-W, Qi D-X, Hou B-Q, Peng R and Wang M 2021 Continuously and reversibly electro-tunable optical nanoantennas based on phase transition of vanadium dioxide New J. Phys. 23 073002
[6] Koivurova M, Hakala T, Turunen J, Friberg A T, Ornigotti M and Caglayan H 2020 Metamaterials designed for enhanced ENZ properties New J. Phys. 22 093054
[7] Sun Z, Martinez A and Wang F 2016 Optical modulators with 2D layered materials Nat. Photon. 10 227–38
[8] Kravets V G, Wu F, Auton G H, Yu T, Imaizumi S and Grigorenko A N 2019 Measurements of electrically tunable refractive index of MoS\(_2\) monolayer and its usage in optical modulators npj 2D Mater. Appl. 3 36
[9] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 Electric field effect in atomically thin carbon films Science 306 666–9
[10] Naumis G G, Barraza-Lopez S, Oliva-Leyva M and Terrones H 2017 Electronic and optical properties of strained graphene and other strained 2D materials: a review Rep. Prog. Phys. 80 096501
[11] Pinto A M, Gonçalves I C and Magalhães F D 2013 Graphene-based materials biocompatibility: a review Colloids Surf. B 111 188–202
[12] Li D and Kaner R B 2008 Graphene-based materials Science 320 1170–1
[13] Akinwande D et al 2017 A review on mechanics and mechanical properties of 2D materials-graphene and beyond Extreme Mech. Lett. 13 62–77
[14] Potsk I S, Chmel S, Chiang C-Y, Zhou W, Popuri S R, Bos J-W G, Misra D K, Morozov Y M and Gregory D H 2019 Toward new thermoelectrics: tin selenide/modified graphene oxide nanocomposites ACS Omega 4 6010–9
[15] Aspemair P et al 2020 Dual monitoring of surface reactions in real time by combined surface-plasmon resonance and field-effect transistor interrogation J. Am. Chem. Soc. 142 11709–16
[16] Grigorenko A N, Polini M and Novoselov K S 2012 Graphene plasmonics Nat. Photon. 6 749–58
[17] Luo X, Qiu T, Lu W and Ni Z 2013 Plasmons in graphene: recent progress and applications Mater. Sci. Eng.: R: Rep. 74 351–76
[18] Low T and Avouris P 2014 Graphene plasmonics for terahertz to mid-infrared applications ACS Nano 8 1086–101
[19] He X, Zhao Z-Y and Shi W 2015 Graphene-supported tunable near-IR metamaterials Opt. Lett. 40 178–81
[20] Aznakayeva D E, Rodriguez F J, Marshall O P and Grigorenko A N 2017 Graphene light modulators working at near-infrared wavelengths Opt. Express 25 10255–60
[21] Ono M, Hata M, Tsunekawa M, Nozaki K, Sumikura H, Chiba H and Notomi M 2020 Ultrafast and energy-efficient all-optical switching with graphene-loaded deep-subwavelength plasmonic waveguides Nat. Photon. 14 37–43
[22] Kravets V G et al 2014 Graphene-protected copper and silver plasmonics Sci. Rep. 4 5517
[23] Likharev K K and Semenov V K 1991 RSFQ logic/memory family: a new Josephson-junction technology for sub-terahertz-clock-frequency digital systems IEEE Trans. Appl. Supercond. 1 3–28
[24] Mukhanov O A 2011 Energy-efficient single flux quantum technology IEEE Trans. Appl. Supercond. 21 780–9
[25] Nevirkovets I P, Chernyashevskyy O, Walter J and Mukhanov O A 2019 Superconducting-ferromagnetic injection-controlled switching device IEEE Trans. Appl. Supercond. 29 1100504
[26] Gusynin V P, Sharapov S G and Carbotte J P 2006 Magneto-optical conductivity in graphene J. Phys.: Condens. Matter. 19 026222
[27] Robertson J 2004 High dielectric constant oxides Eur. Phys. J. Appl. Phys. 28 265–91
[28] Hanson G W 2008 Dyadic Green’s functions for an anisotropic, non-local model of biased graphene IEEE Trans. Antennas Propag. 56 747–57
[29] Noh E-K, Boampong A, Konno Y, Shibasaki Y, Lee J-H, Choi Y and Kim M-H 2021 Effect of buffer layer capacitance on the electrical characteristics of ferroelectric polymer capacitors and field effect transistors Materials 14 1276
[30] Lalanne P, Yan W, Vynck K, Sauvan C and Hugonin J-P 2018 Light interaction with photonic and plasmonic resonances Laser Photon. Rev. 12 1700113