Nanostructured arrays of doped semiconductors for IR nanophotonics

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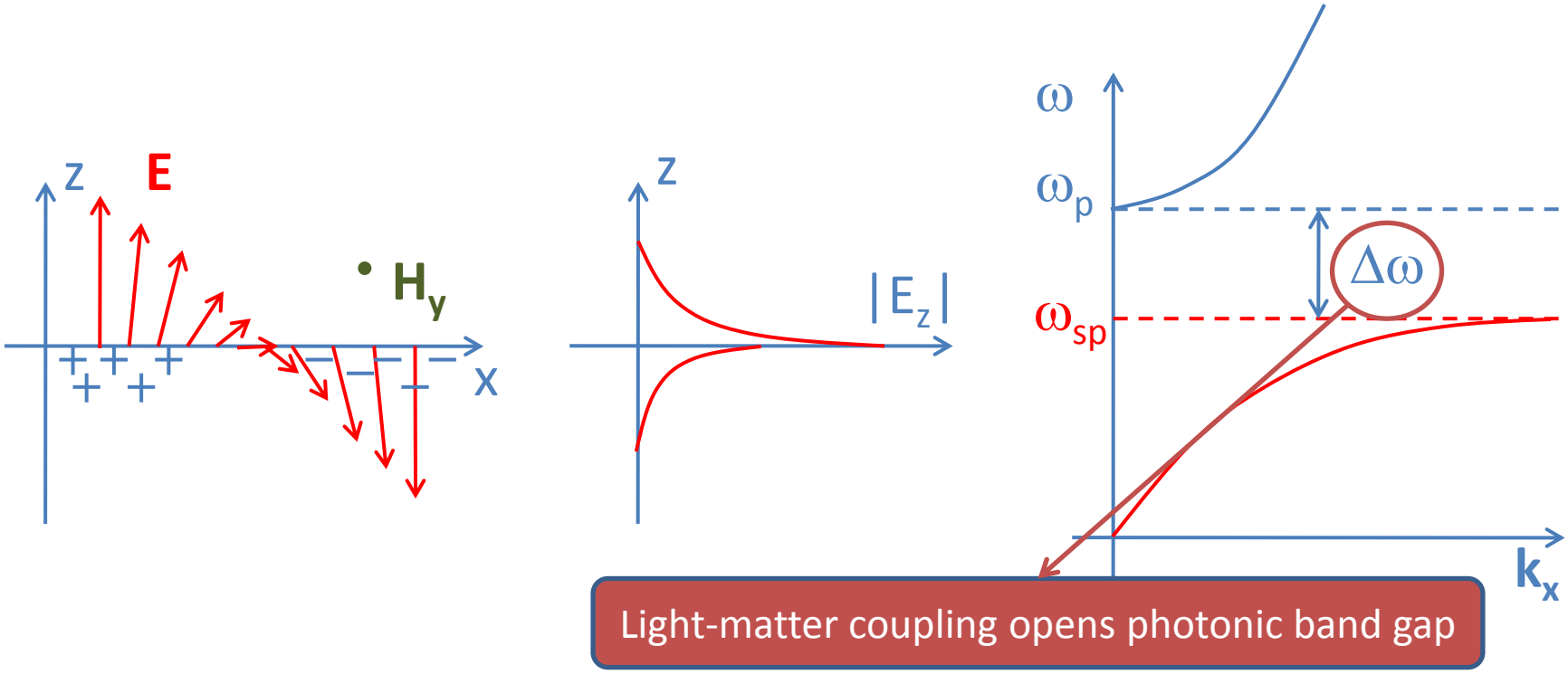
Our motivations

- Surface plasmon is an hot topic
- Essential works on noble metals (> 36000 articles)
  - Visible range
  - Realization

- Surface plasmon on doped semiconductors (> 130 articles)
- Few works on periodic arrays of doped SC (NIM *Nat.Mat. 6, 946 (07)*)
- Interest of highly doped semiconductors for IR applications
  - Adjust the plasma frequency
  - Work around the plasma frequency

- We propose an analytic model which describes the light-matter coupling with arrays of doped/undoped semiconductors

Surface plasmon polariton



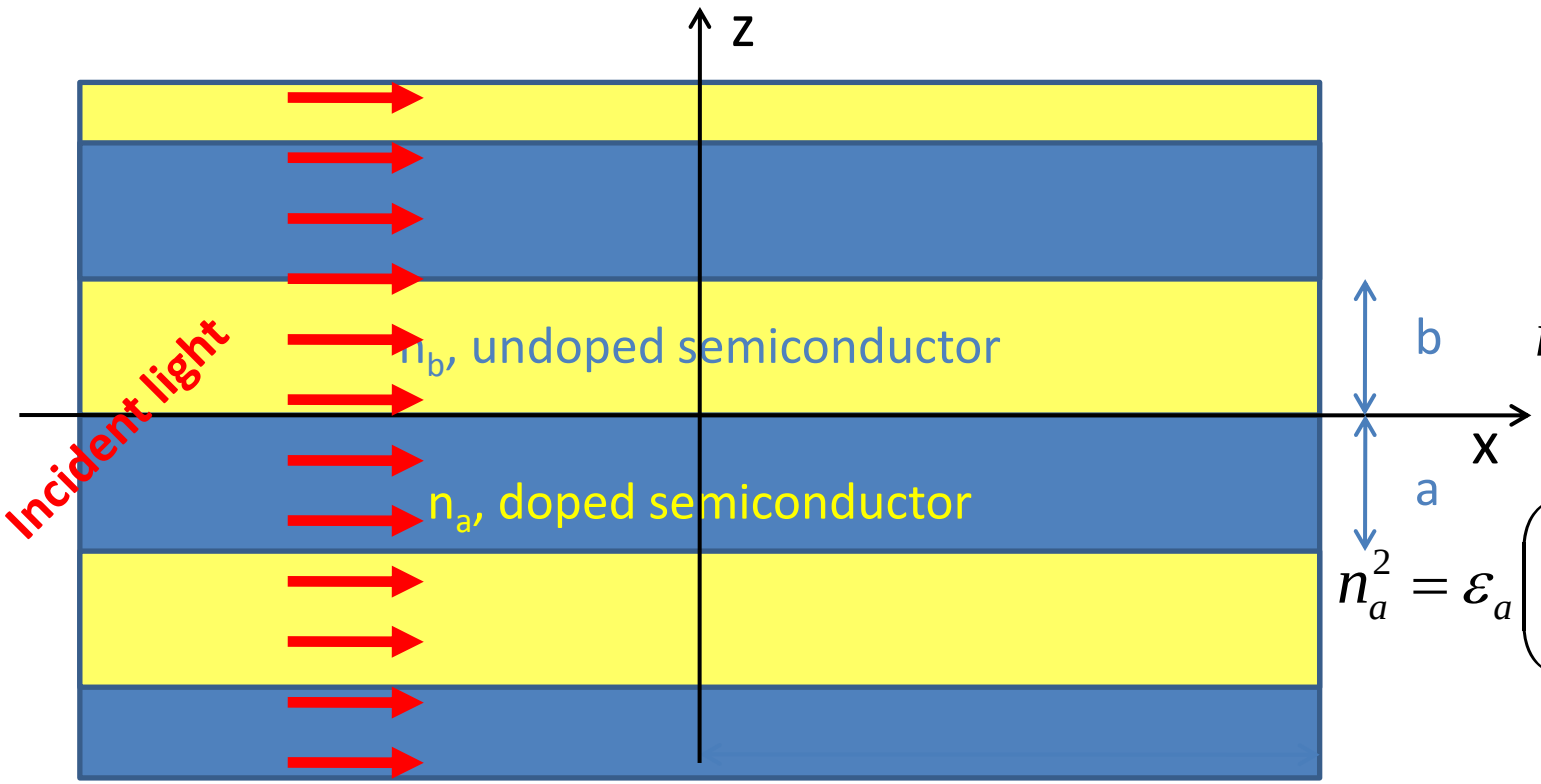
Light-matter coupling opens photonic band gap

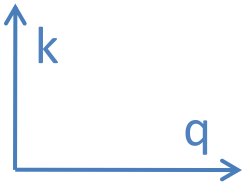
In the case of surface plasmon polariton, the light-matter coupling is huge.

This 2D system is difficult to excite optically.

How to circumvent this difficulty?

Problem definition





$$n_b^2 = \varepsilon_b$$

$$n_a^2 = \varepsilon_a\left(1 - \frac{1}{\omega(\omega + i\gamma)}\right)$$

Normalization

All frequencies are normalized to the plasma frequency ω_p, the wavenumber to $k_p = \omega_p/c$, the lengths to k_p^{-1}, and time to ω_p^{-1}.

Resolving Maxwell equations in TM polarization

$$\varepsilon_b k_a \tan\left(a \cdot k_a/2\right) + \varepsilon_a k_b \left(1 - \frac{1}{\omega\left(\omega + i\gamma\right)}\right) \tan\left(b \cdot k_b/2\right) = 0$$

$$\varepsilon_a k_b \left(1 - \frac{1}{\omega\left(\omega + i\gamma\right)}\right) \tan\left(a \cdot k_a/2\right) + \varepsilon_b k_a \tan\left(b \cdot k_b/2\right) = 0$$

The main approximation a and b < k_p^{-1}

↓

tan (a k_a /2) ~ a k_a /2 and tan (b k_b /2) ~ b k_b /2

$$k_a^2 = \varepsilon_a\left(\omega^2 - 1\right) - q^2$$

$$k_b^2 = \varepsilon_b \omega^2 - q^2$$

We obtain the relation dispersion for the wave vector **q**

$$q^2 = \varepsilon_{eff}\,\omega^2$$

Main results

$$q^2 = \varepsilon_{eff}\,\omega^2$$

In TM polarization

$$\varepsilon_{eff} = \varepsilon_{TM}\,\frac{\omega(\omega+i\gamma)-1}{\omega(\omega+i\gamma)-\omega_r^2}$$

$$\varepsilon_{TM} = \frac{(a+b)\varepsilon_a\varepsilon_b}{a\varepsilon_b + b\varepsilon_a}$$

$$\omega_{sp}^2 = \frac{b\varepsilon_a}{a\varepsilon_b + b\varepsilon_a}$$

Ionic-crystal behaviour

In TE polarization

$$\varepsilon_{eff} = \varepsilon_{TE}\left(1-\frac{\omega_t^2}{\omega(\omega+i\gamma)}\right)$$

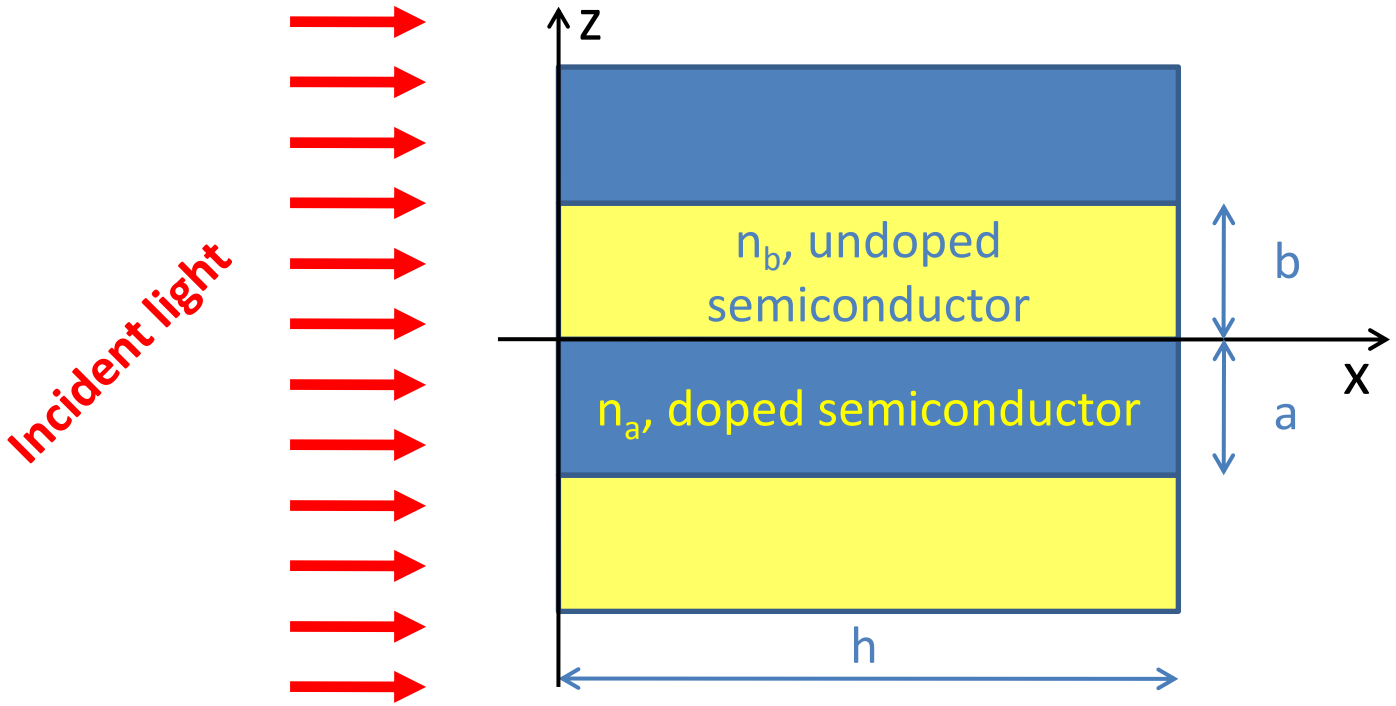
$$\varepsilon_{TE} = \frac{(a\varepsilon_a + b\varepsilon_b)}{a+b}$$

$$\omega_{pp}^2 = \frac{a\varepsilon_a}{a\varepsilon_a + b\varepsilon_b}$$

Metal behaviour

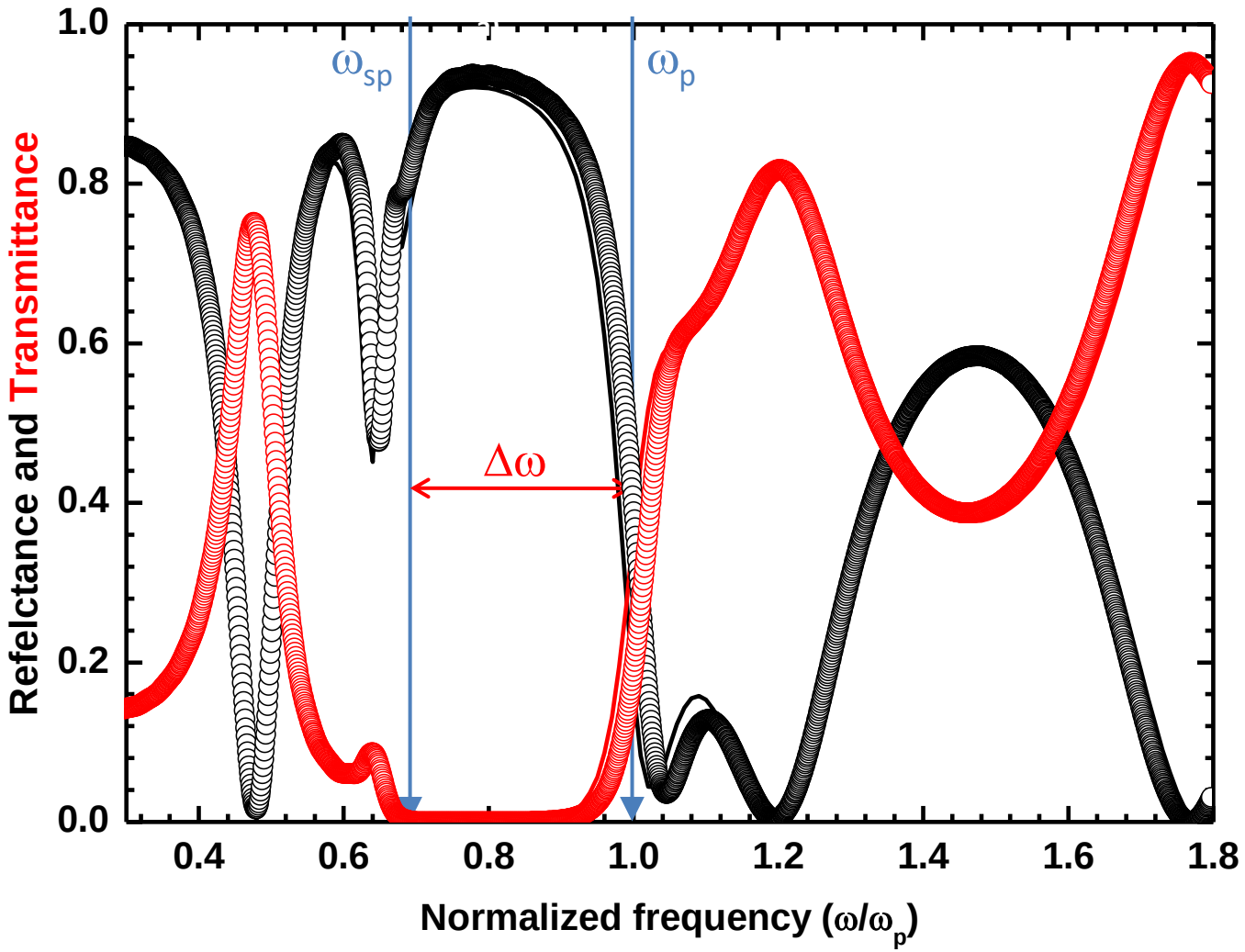
Model vs Simulation

All simulations are realized with the following parameters :
ω_p= 3.42 10^{14} rad/s, $\varepsilon_a = \varepsilon_b$ = 11.7, a = b = 0.2 µm, h = 1 µm and
$\gamma = 10^{13}$ rad/s



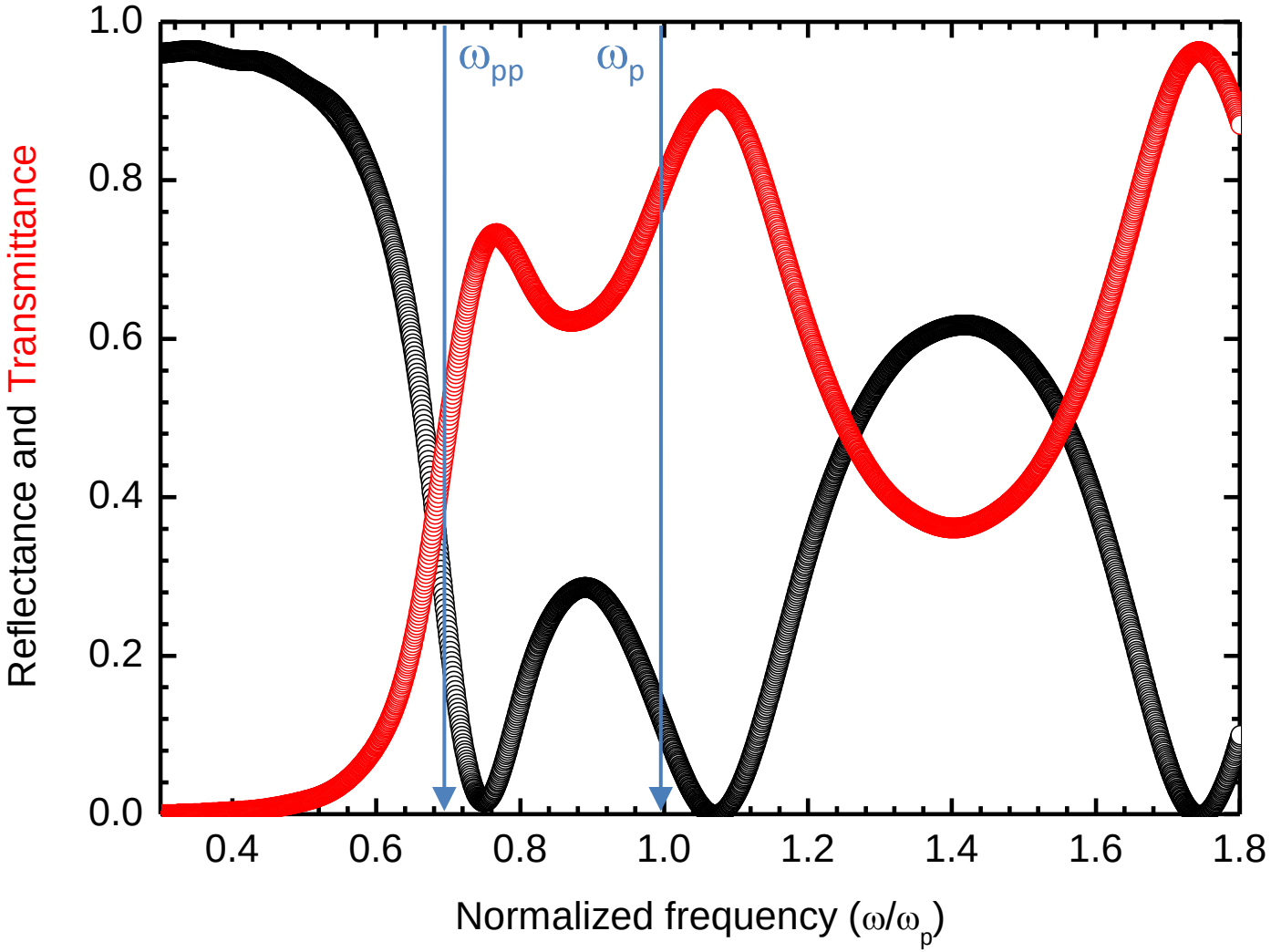
J.Léon PRB 82 195301 (2010)

Model vs Simulation in TM polarization



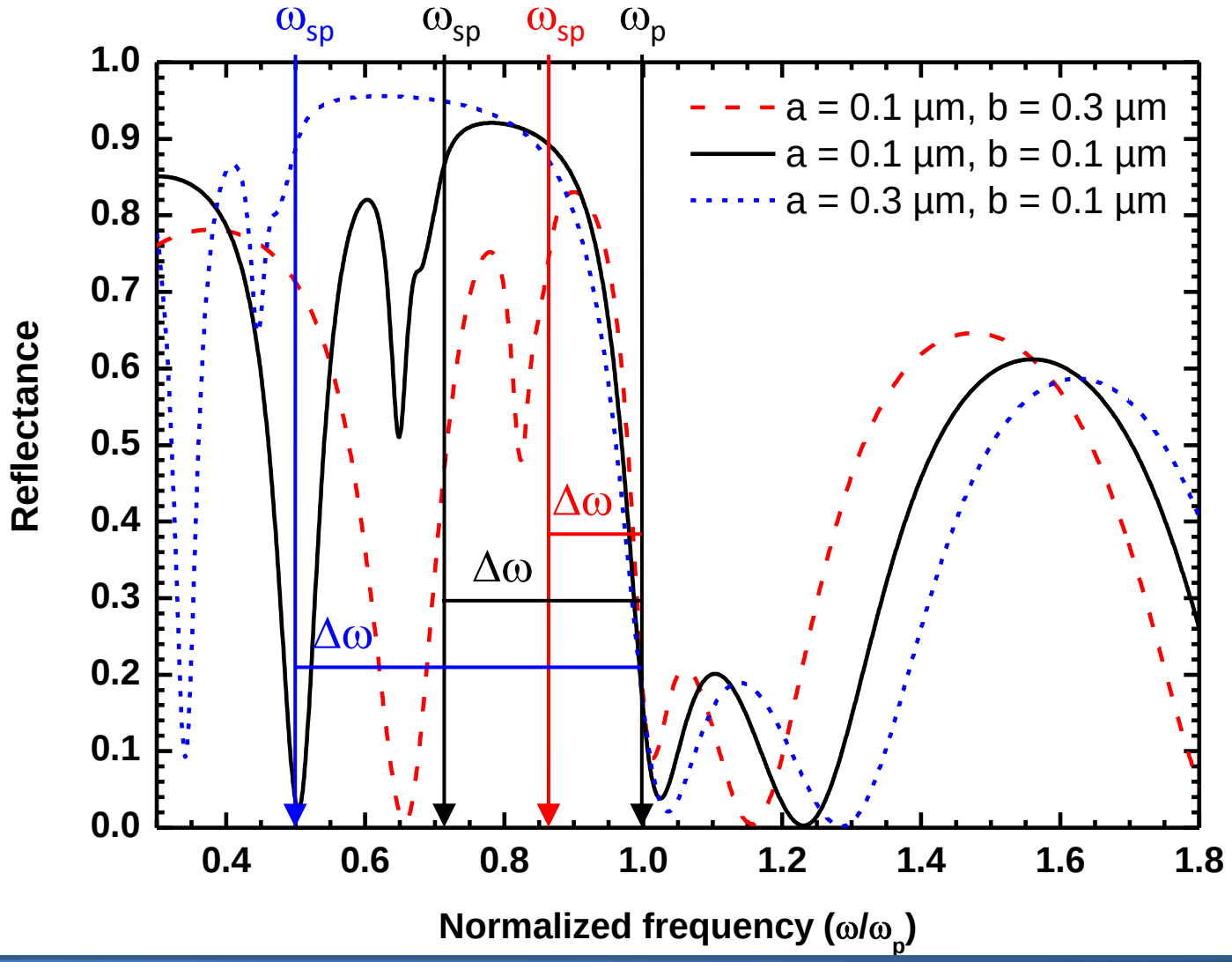
- Huge light-matter coupling with a photonic band gap $\Delta\omega = 0.3$
- Good agreement between model & numerical simulation

Model vs Simulation in TE polarization



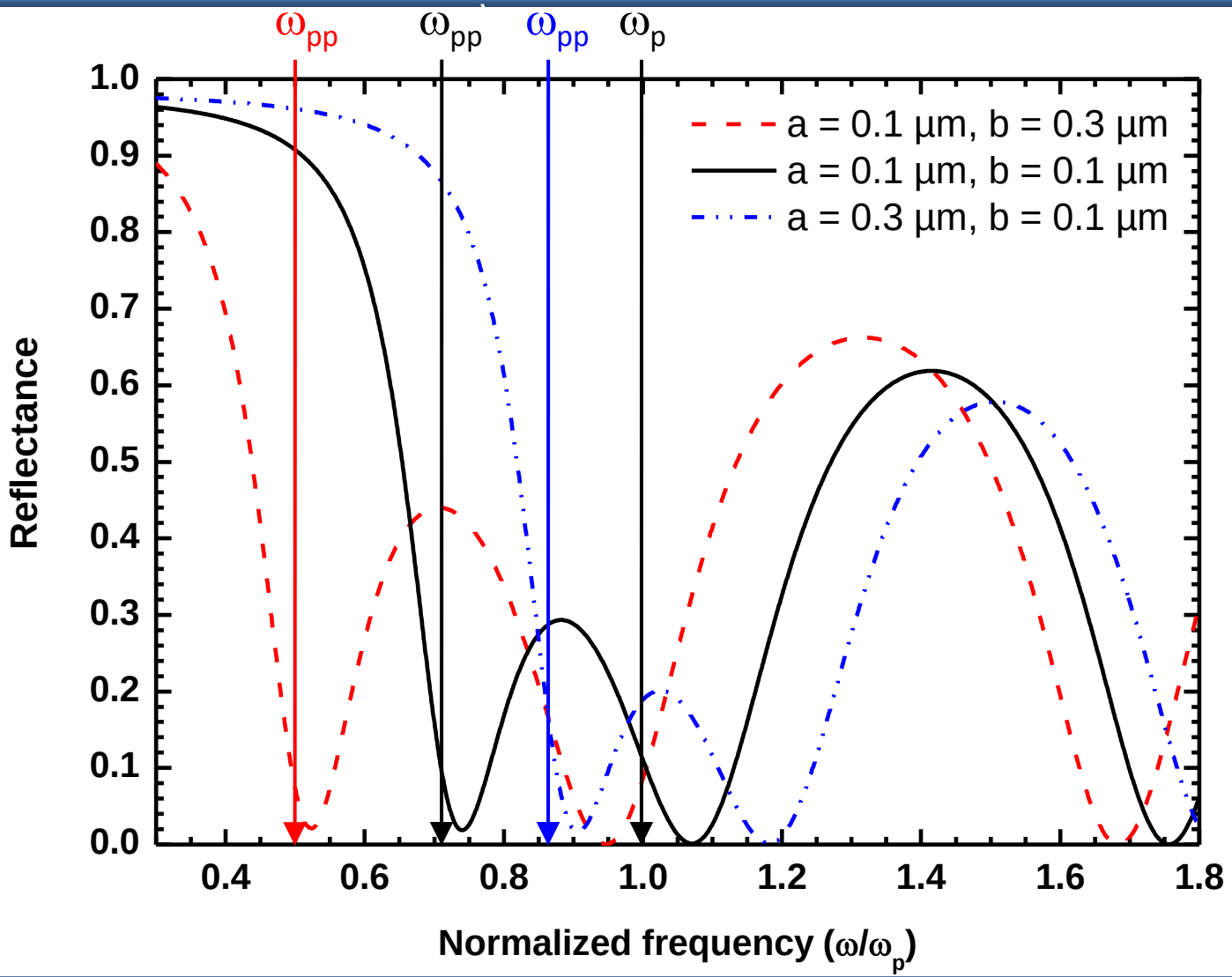
- Metallic behaviour
- Possibility to define a plasma frequency for a pseudo-volume plasmon

Varying the geometrical parameters in TM incident plane wave



- The smaller the metal (a), the smaller the photonic band gap $\Delta\omega$.
- The larger the metal (a), the larger the photonic band gap $\Delta\omega$.

Varying the geometrical parameters in TE incident plane wave



- The smaller the metal (a), the lower the pseudo-plasma frequency
- The larger the metal (a), the higher the pseudo-plasma frequency

Conclusion

- Validation of the model in the long-wave limit
  - In TM polarization the metamaterial is like a ionic-crystal
  - In TE polarization the metamaterial is like a metal
- Design structures with the expected $\Delta\omega$
- Beyond the long-wave limit it is necessary to use the complete model
- Future works:
  - Exploring the possibilities of this model
  - Experimental demonstrations

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