Thin film interference: an experiment with microwaves and paraffin oil

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Introduction

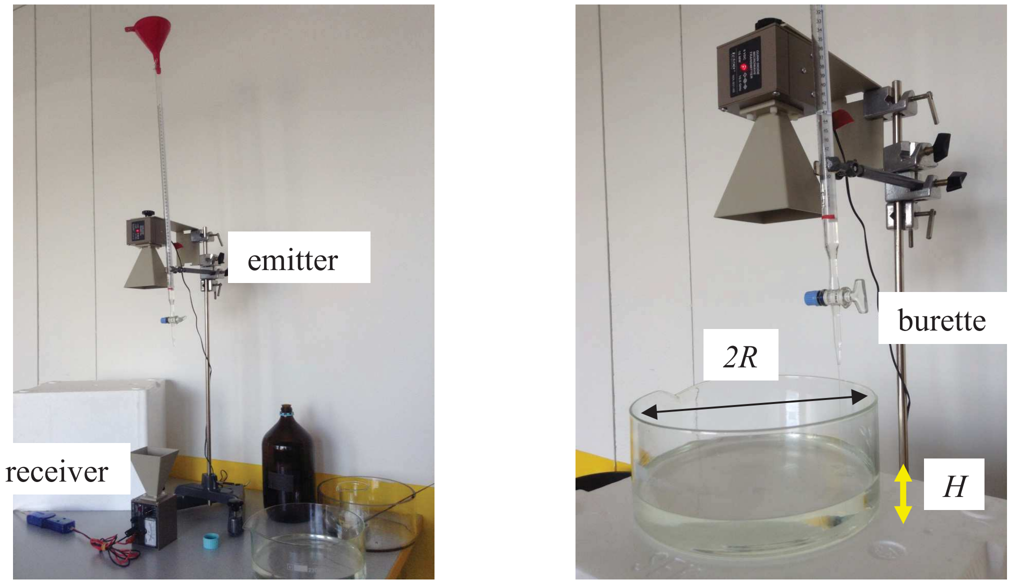
Thin film interference manifests itself in a wide range of visually pleasing situations in everyday life (in the coloured effects caused by a drop of oil on water, in soap bubbles, etc.) and is also involved in important technical applications (semi-reflecting mirrors, anti-reflection lenses, etc.). Yet, despite its familiarity, high school students are rarely asked to consider this common phenomenon, in particular from an experimental point of view.

In this paper we present an experiment to test quantitatively the *thin film interference relation.* Since experiments with visible light involve layer thicknesses too small to be managed in a high school laboratory, we use microwaves of wavelength $\lambda = 2.85$ cm. Furthermore, we choose to work with paraffin oil[1], so that we can easily change the thickness of the layer. As expected, the measured intensity of the transmitted wave shows a modulation with the thickness of the layer, so that an accurate data analysis enables us to determine the refractive index of the paraffin oil in the chosen wavelength range. The value obtained also corresponds nicely with the measurements made using a Michelson & Morley interferometer.

From a didactical point of view, this experiment can be considered as a quantitative alternative to those commercially available, showing interference fringes with visible light and thin wedge of air. The advantages are: 1) by changing the thickness themselves, students discover step by step the modulation of the intensity of the transmitted signal; 2) the expression *thin film* emerges immediately as a concept that correlates the thickness of the layer with the wavelength we are considering; 3) the experiment can also be seen as an introduction to relevant experimental techniques, such as time resolved reflectivity[2], or to interference experiments at low intensity, as those illustrated by R.P. Feynman in the first chapter of his QED[3].

Experimental set up

In order to have a layer of paraffin oil with variable thickness H we arranged the equipment as showed in Fig. 1. A microwave transmitter and a receiver[4] are mounted vertically on a rod, in such a way that it is possible to insert between them a glass vessel of suitable diameter[5] sustained by a box of expanded polystyrene, a common material transparent to microwaves. Sub-liquid paraffin is then released in the glass vessel measure after measure, in small amounts of 25 mL at a time, using a precision burette. After each addition of paraffin, the intensity of the transmitted signal is registered with a data acquisition system[6], while the actual thickness of the layer can be calculated from the total volume of paraffin oil introduced and the geometrical properties of the employed cylindrical vessel.



a) b)

Figure 1 - Experimental apparatus: a) the entire device with emitter and receiver; b) detail with the vessel and the burette used to add controlled quantities of paraffin oil; the receiver is inside the polystyrene box.

Measurements and results

Since the purpose of our experiment is to show how changes in the layer thickness generate (local) minimums and maximums in the transmitted intensity, we have chosen the simplest set up (Fig. 1). This way, the measured intensity values may be distorted by some factors, such as the angular distribution of the emitter, the partial focusing due to the glass vessel or the chosen geometry, or the not perfect linearity of the receiver response. These aspects can be partially improved by using wax lenses, but it isn't worth the trouble, since the intensity distortion doesn't affect nor the position of the minimums and maximums, neither therefore the analysis which leads to the *thin film relation* we are looking for.

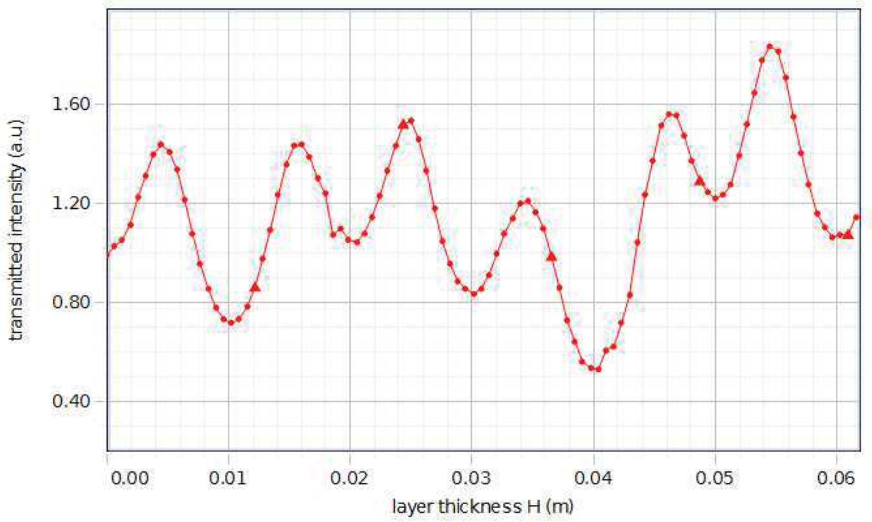


Figure 2 - Intensity of the transmitted signal vs. paraffin oil layer thickness H. After every addition of 25 mL a measurement has been done. The intensity should be considered in arbitrary units.

Typical measurements are plotted in Fig. 2: changing the thickness of the paraffin oil layer, the intensity of the transmitted signal shows clear maximums and minimums. As a (reproducible) consequence of the experimental set up, the intensities of different maximums or minimums have different values. In order to interpret the data, we use the simple *model* of two interfering *plane waves*. Inside the layer a multiple reflection takes place (Fig. 3): since the intensity falls considerably with each internal reflection, we take into account only the first two transmitted contributions[7]. A change in the thickness H then induces changes in the *interference condition*, so that even if the irregular behavior of the intensity is not predicted, it doesn't prevent us from determining the values of H at which we observe maximums and minimums.

In particular, defining n as the refractive index in the given wavelength range, an increment ΔH of the thickness of the paraffin oil layer changes the optical *path difference* between the two interfering contributions crossing the layer: assuming normal incidence, in situation A) of Fig. 3, the optical path difference is $\Delta s_A = 2Hn$, while in situation B) it becomes $\Delta s_B = 2(H + \Delta H)n$, so that, increasing the thickness by ΔH, the *change* in the optical path difference is $2n\Delta H$.

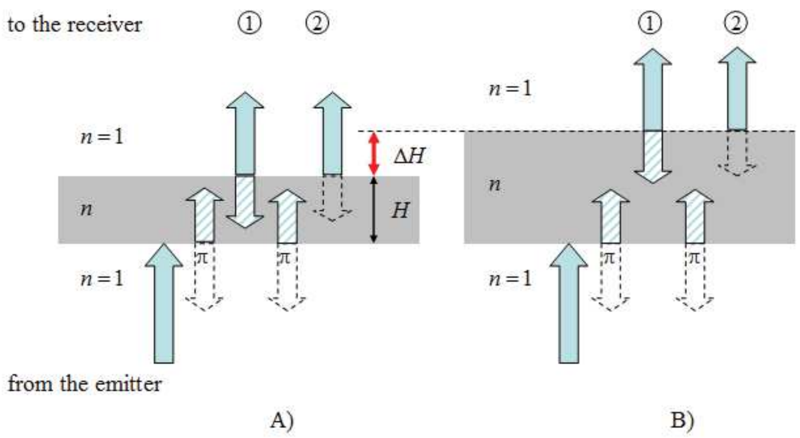


Figure 3 – Changes in the optical path difference as a consequence of the increment ΔH of the liquid layer thickness under normal incidence conditions: with each change of optical medium we have both transmission and reflection (when occurring, π expresses the phase shift caused by reflection). The contributions originated in the different processes are represented, for the sake of clarity, as arrows progressively shifted to the right (dashed arrows refer to those that are not of interest in our experiment). Since we look only at the changes in the interference condition between the transmitted contributions 1 and 2, only the changes in ΔH are relevant.

Since an increment of λ/2 in the optical path *difference* turns, for instance, a constructive interference condition into a destructive one, we get the relation:

$$2\,n\,\Delta H = \frac{\lambda}{2}\Delta k \ , \tag{1}$$

where k numbers the consecutive positions of the extremes (both, minimums *and* maximums).

In Fig. 4 we plot the values of the thickness H at which we observe extremes of the measured intensity as a function of k. The linearity proves that the two plane waves interference model can be successfully applied in the present situation.

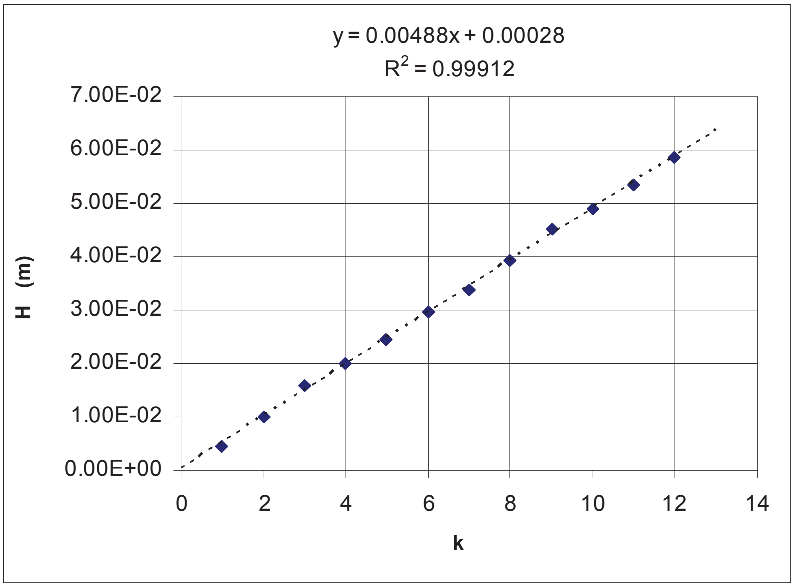


Figure 4 - Thickness of the paraffin oil layer H associated to minimums and maximums of the measured intensity numbered by k. Data shows a linear relationship (dashed line).

Relation (1) allows us therefore to determine the refractive index n from the slope $\Delta H/\Delta k$. Knowing the frequency of the emitted signal (10.5 GHz), i.e. the wavelength $\lambda = 2.85$ cm, and calculating the slope as $\Delta H/\Delta k = (4.88 \pm 0.14)\ 10^{-3}$ m, we determine the *refractive index* of the paraffin oil:

$$n = \frac{\lambda}{4\,\Delta H / \Delta k} = 1.46 \pm 0.04\,. \tag{2}$$

Measurement of the refractive index with the Michelson & Morley interferometer

From a didactical point of view it could be relevant to have more experiments allowing the students to verify the same result. To measure the refractive index of the paraffin oil in the same wavelength range, we use therefore a suitable Michelson & Morley interferometer[8] too. In the first step (Fig. 5a and Fig. 5b) we insert an empty container along one of the microwaves' paths, adjusting the mirrors M_1 and M_2 in order to have a "zero" output from the receiver (destructive interference, Fig. 5a).

In the second step (Fig. 5c and Fig. 5d), we fill the container with paraffin oil: now we register a non zero output signal (Fig. 5c). Indeed, filling the container, we have extended the optical path by the quantity:

$$2\,(n-1)\,D\,, \tag{3}$$

where n is the refractive index of the paraffin oil (at $\lambda = 2.80$ cm), and D is the known thickness of the container. Given that the initial (destructive) interference condition can now be recovered by means of a *forward* displacement Δx of the mirror M_2 (Fig. 5d), we get:

$$2\,(n-1)\,D = 2\,\Delta x\,. \tag{4}$$

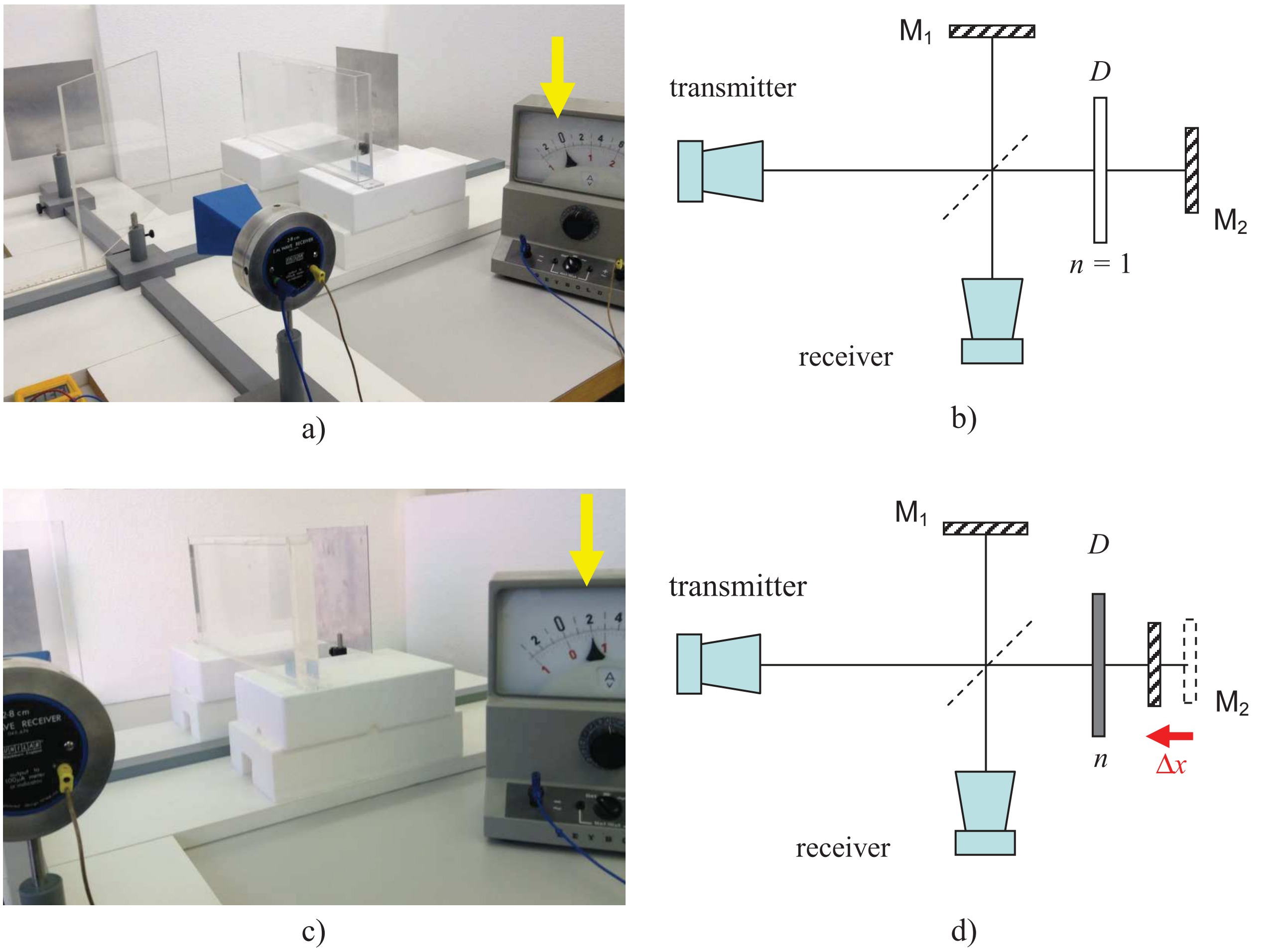


Figure 5 – The Michelson & Morley interferometer for the measure of the refractive index of the paraffin oil.

From our measurements we get $D = (28.5 \pm 0.5)$ mm and $\Delta x = (12.5 \pm 0.2)$ mm, so that:

$$n = 1 + \frac{\Delta x}{D} = 1.44 \pm 0.05\,, \tag{5}$$

a result which corresponds nicely with the previously determined value of the refractive index of the paraffin oil.

Note added

We chose to work with paraffin oil because we usually use (solid) paraffin for other experiments with microwaves. Our referees, however, were worried about the use of paraffin oil, citing availability, cost and security issues, and suggested trying our experiments also with other oils. Even though, to our knowledge, *subliquid paraffin* is not subjected to particular security restrictions[1], we repeated our measurements with the more common and cheaper sunflower oil. Our results show that this oil can be used effectively with acceptable results, but there is also some didactical inconvenience, because of its refractive index in the microwave range used (we measured 1.55 ± 0.05) – quite different with respect to the refractive index in the visible range (1.46 ± 0.03, measured from the limit angle) – and fewer *maxima* and *minima* for data analysis, since, probably because of absorption, over a thickness of only few centimetres the intensity of the signal falls considerably.

Acknowledgements

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Reference and notes

1. Paraffin oil (*paraffinum subliquidum*) is a non-flammable mineral oil also used for medical purposes. See: https://en.wikipedia.org/wiki/Liquid_paraffin_(medicinal) (13/03/2015).
2. F. Corni, E. Mazzega, M. Michelini, G. Ottaviani, *Understand time resolved reflectivity by simple experiments,* in Proceedings of the GIREP conference on Physics Education "Light and Information", Braga, 1993. Available at: http://www.pse.unimore.it/site/home/publications.html (13/03/2015).
3. R.P. Feynman, *QED – The strange theory of light and matter,* Princeton, 1985.
4. We used the PASCO transmitter and receiver from the WA-9314B Microwave Basic System.
5. The diameter *2R* of the vessel should, of course, be chosen according to the *local* width of the incident wave, i.e. the width in the position in which the vessel is placed. Considering the geometry of our set up, a diameter of 23 cm gave us satisfactory results.
6. Since we recorded the output signal of the receiver with a PASCO PS-2115 Voltage/Current sensor without any calibration, the values should be considered in arbitrary units. Measurements were collected with the *Keep mode* function of the Capstone software.
7. Since we are interested only in the change of the interference condition depending on the thickness of the paraffin oil layer, in our model we do not include the additional *flat* and *smooth* layer of glass at the bottom of the vessel.
8. We used a UNILAB microwave system, with a 2.80 cm wavelength.