An easy physics outreach and teaching tool for holography
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Abstract: in the framework of scientific outreach at the "Maison des Sciences" of the Aix-Marseille University, we created a teaching kit for holography contained in a small case. It includes all the required equipment to produce holograms almost anywhere with a simple optical assembly with a very good vibration tolerance. The fundamental principles of holography and several applications are illustrated through simple experiments: reflection Denisyuk holograms, angular multiplexing, notch filters, holographic interferometry and diffraction holographic gratings. It is possible to use this tool for several purposes: science outreach, teaching for undergraduate and graduate students and continuing education. In this article, we explain the basis of holography, how the kit works, and give some applications and results that can be done with it.

1. Introduction
D. Gabor, a Hungarian-born British physicist, invented the principle of holography in 1948 while he was looking for an electronic microscopy resolution enhancement [1]. He received the physics Nobel Prize for is work on holography in 1971. The three-dimensional pictures are produced with a coherent light source (laser) and are particularly realistic. By using three lasers, one for each of the wavelengths of the primary colors, it is impossible to differentiate the real object and its hologram, provided that the hologram is properly illuminated. Holograms intrigue and allow addressing many physical principles of varying degrees depending on the audience: laser properties, colors, coherence, interference and interferometry, HVD (Holographic Versatile Disc), etc. However, the technics to produce holograms are usually very sensitive to parasite vibrations. According to many books, it is almost impossible to produce a hologram in an environment where all sources of vibration are not perfectly controlled. Depending on the type of holographic device, a movement of a few tenths of micrometers may be enough to fail the experiment.

The kit for holography presented in this paper allows making very good quality holograms (Fig. 1) almost anywhere, if the room is dark enough and has an electricity access. The assembly is simple and optimized to be extremely robust with respect to vibrations. No need to use any device to palliate parasite vibration sources. The technics is based on reflection holograms invented by Y. Denisyuk [2], which was inspired by G. Lippmann work on interferential color photography [3]. The holograms are observable in white light and illustrate several physics principles like holographic interferometry, angular multiplexing used in HVD (Holographic Versatile Disc), "notch" filters (Raman spectroscopy) and diffraction holographic gratings.
(passive spectroscopy). After a short introduction on the principles of holography, we present the device included in the kit and the experiments possible to do with it, depending on the audience.

2. Hologram production principle

Holography is based on a simple principle: the interference between two coherent light beams. On Fig. 2, the beam from the laser L is divided in two parts by an optical system S and spreads out over the object O as well as on the photosensitive plate P. The "Object Beam" OB is the beam obtained by the diffusion/reflection of the light on the object, while the "reference beam" RB comes directly from the laser. The mean angle between the object and reference beams is $\theta$. This angle is important for angular multiplexing principles (part 4). Interferences between the two beams OB and RB occur only if their path difference is less than the coherence length. This particular length correspond to $L_c=c/\Delta\nu$, where c is the speed of light, and $\Delta\nu$ the spectral width of the laser. The experimental setup used in the holographic case only needs a coherence length larger than 1 cm. By construction, the low power HeNe lasers we use have a coherence length much larger than this.

When the object is a simple front surface mirror, a periodic modulation of the light intensity is recorded on the photosensitive plate due to the phase shift between RB and OB. If the object is not plan, beam wave front of OB is deformed, and the resulting interference pattern becomes more complex. The fundamental idea of holography is to record this phase variation relatively to the reference beam RB. Once developed, the hologram illuminated with the reference beam diffracts light just like the object. Then, unlike a photograph, a hologram contains information on the object relief. For diffusive object, it is important to note that there is information redundancy, because every point of the object sends back laser light on a large part of the photosensitive plate. People interested in a complete description of holographic technics should refer, for example, to G. Saxby’s book [5].
3. Teaching kit for holography description

The teaching kit for holography has been developed in 2010 after the CETSIS congress [6] dedicated to didactic experiments. The dimensions of the holographic case are 34cm×25cm×16cm, and includes absolutely all the necessary items to produce a hologram almost anywhere. The case includes a 0.8 mW gas laser HeNe emitting at 632.8 nm (Class IIIa). With a power under 1mW, it is possible to decrease the risk linked to highly collimated beam. This type of gas laser has a good coherence length, especially as its power is low. The laser requires no special precautions with regards to its stability. It is possible to use a laser diode, which is much cheaper. However, diodes characteristics are extremely sensitive with respect to temperature changes, which may strongly decrease the hologram success rate.

The Fig. 3 shows the experimental setup, and corresponds to a single beam Denisyuk hologram setup. The laser light is spread with a lens and is directed upwards with the aid of a 45° mirror, inspired from a periscope reflective mount system. The photosensitive plate and the object are placed directly on the flat mirror mount, as indicated on Fig. 3. This mirror mount is
the central part of the experimental setup, which is made by the mechanic team of the Aix-
Marseille University. Unlike the setup shown on Fig. 2, there is no need to physically divide the
laser beam in two parts. The object beam is the one which is reflected/diffused by the object and
which is coming back towards the plate, while the reference beam is the part of the one directly
coming from the laser. In holography, stability is crucial, but only after the laser beam division
[5]. In a single beam Denisyuk hologram setup, this only happens when the beam is crossing the
plate. Moreover, the plate and the object are stabilized with respect to each other thanks to
gravity. Thus, hologram can be produced anywhere (Classroom, hall, Kitchen, etc.), with almost
any vibration condition. The produced holograms can be observed with white light spot, which is
an important asset for direct observation after its completion.

4. Teaching kit for holography applications

The first aim of the teaching kit for holography is to produce simply good quality
holograms, in any room with correct obscurity conditions, a power source for the laser, and water
access for hologram development. Producing a hologram is an extremely rewarding experiment.
Therefore, it is interesting to use it as teaching demonstration, or as practical experiment for
undergraduate student.

For outreach purpose, a simple hologram can be produced during a workshop of 45
minutes. This includes basic explanations on holography physics as well as holograms
production. A group of 20 primary school, junior high school and high school students can attend
the workshop at the same time. To arouse their curiosity and give them information accessible to
their levels, the workshop content is tailored to the level of students. With a success rate of
almost 100%, students who realize a hologram are systematically proud of their production.
Thus, they are in good conditions to go further in the physical notions on which holography is
based.

Beyond the simple realization of a hologram, it is possible to make several experiments
illustrating the applications of holography:

- Holographic interferometry, used in mechanical stress diagnostics,
- Angular multiplexing, used in data storage (Holographic Versatile Disc),
- « Notch » filter, used in Raman spectroscopy,
- Diffraction holographic grating, used in passive spectroscopy.

Holographic interferometry is the technics that introduced holography in the field of
industry in 1965. The researchers found that if the object moves a few micrometers when the
hologram is realized, interference fringes associated with this movement appear. It is possible to
measure micrometrical deformations of any object by this technique [7]. To realize such
experiment with the kit, it is necessary to make a double exposure hologram of a metallic foil F
placed just above the photosensible plate and fixed at one extremity (Fig.4). Between the two
exposures, the other extremity of the foil is translated of a known distance \( d_{\text{mic}} \) with a calibrated micrometer head \( C \) fixed on the mirror mount \( M \). After the development, the two holograms shifted of a small distance will create secondary interference consisting of dark/light fringes superimposed on the foil hologram. The foil shift \( d_{\text{holo}} \) can be deduced by counting the number of dark fringes between its fixed part and the translated part. For the \( N^{\text{th}} \) dark fringe, we have:

\[
d_{\text{holo}} = (N-1) \frac{\lambda}{2} + \frac{\lambda}{4}
\]  

with \( \lambda \) = laser wavelength. This result can be compared to the translation of the calibrated translation device \( d_{\text{mic}} \). The Fig. 5 shows typical results obtained by first year students at the Aix-Marseille University. They found a good linearity between the two-measurement methods, validating the theoretical calculation.

**Figure 4**: Table of interferometry measurement. P: Photosensitive plate. F: metallic foil, fixed on the left side. C: calibrated micrometer head, moving the foil right side.

**Figure 5**: measured displacement \( d_{\text{holo}} \) of a metallic foil deduced from its double exposure hologram versus real displacement \( d_{\text{mic}} \) measured with a calibrated micrometer head (o). The line represents the ideal case \( d_{\text{holo}} = d_{\text{mic}} \).

Information storage with semiconductor memories or disc (DVD, blu-ray, etc.) use “surface” technology. Nowadays, these technologies are well known and their capacities are close to the theoretical limit. The holography allows storing data in “volume”, which increases
greatly the density of information. Holographic Versatile Disc (HVD) uses this principle to store data. Moreover it is possible to increase the data density thanks to angular multiplexing. This technics rely on a singular property of holography: by changing the reference beam angle $\theta$ between each exposure, it is possible to record several data on the same photosensitive plate. After the development, hologram returns particular data depending on the reference beam angle used to read the disc. The kit for holography allows illustrating this angular multiplexing principle. With one photosensitive plate, two holograms are produced with two different reference beam angles. For this, a wedge is placed below one edge of the photosensible plate and a new object is put on it between two exposures to the laser.

A third application of the kit is the creation of a “Notch” filter, which is blocking a particular frequency range with much steeper fronts than conventional interference filters. These filters are used in Raman spectroscopy, where it is necessary to distinguish scattering spectra very close to the excitation source. It is possible to produce such filter with the kit, simply by producing a hologram of a front mirror put on the photosensible plate. After the development, the hologram reflects light like the object, but only on a spectral band $D_1$ around the laser wavelength. As shown on Figure 6, it is possible to measure the transmittance of the obtained Notch filter with a white light source and a small spectrometer (not included in the kit).

**Figure 5**: transmittance of a Notch filter made with the teaching kit for holography. The holographic plates are pre-swelled so that the centered wavelength of the filter is shifted of $70 \text{ nm}$ from the initial HeNe laser wavelength ($632.8 \text{ nm}$).
Figure 6: Table of diffraction grating. M1: main mirror. M2: additional mirror on a rotating system

A fourth application of the teaching kit for holography is the realization of holographic diffraction gratings widely used in passive spectroscopy. For this, a front surface mirror is fixed in front of the entrance hole of the mirror mount to deviate a small part of the incoming laser beam (Fig.6). A mechanical device allows its precise positioning. This part of the beam encounters the undeflected laser beam on the plate with a phase shift. This leads to the creation of interference fringes which can diffract incident light. The distance $d_g$ between two successive fringes, and as a consequence, the groove spacing can be deduced from the following relation:

$$d_g = \frac{\lambda}{2 \sin \left( \frac{\alpha}{2} \right)} \tag{2}$$

With $\alpha$ = mean angle between the two phase shifted laser beams. This experiment illustrates the principle of holographic diffraction gratings realization, and it is possible to clearly observe the first order diffraction spectrum of an incident white light. More precisely, we can calculate the mean groove spacing $d_g^{\exp}$ by measuring the first order diffraction angle $b_2$ of the collimated HeNe laser beam of the kit with an incident angle $b_1$ with respect to the normal $b_2$:

$$\sin(b_1) + \sin(b_2) = \frac{\lambda}{d_g^{\exp}} \tag{3}$$

Experimentally, we obtain around 1200 grooves per mm. If we use the relation (2), this corresponds to a mean angle $\alpha$ of 46°, which is coherent with the global orientation of the mirror. A more precise measurement of $d_g^{\exp}$ can be done by the use of other lasers at different wavelengths, for example a Blu-ray diode ($\lambda=405$ nm) and a Nd:YAG green laser module ($\lambda=532$ nm). Moreover, it is possible to study the evolution of $d_g^{\exp}$ with the mean angle $\alpha$ by making several diffraction gratings with different angles between the two parts of the laser beam.

These experiments have been proposed with success to physics students at the Aix-Marseille University. The experimental device was installed on common tables, without
particular precautions against vibrations. They allow precise measurements and show several important current applications of holography.

5. Conclusion

The described teaching kit for holography is used since several years at the Aix-Marseille University for student's physics projects. It provides pedagogic subjects for undergraduate students with no particular need for active of passive anti-vibration mount. It is possible to develop, with educational goals, more complex experiments based on this kit: color holography (wavelength multiplexing), good quality interferential filters with central length filter control, etc. These kind of experiments may be used as a “semester project” for undergraduate as well as graduate student. In this case, students may develop the full experiment by themselves, typically one half day per week. Moreover, the optical assembly may be used for outreach purpose, like public exhibition, workshop, science festival, conferences, etc. Finally, the holographic kit may be used for junior high and high school teacher training. Thus, in an outreach point of view, teachers can teach their students how produce hologram themselves. Currently at Aix-Marseille University, two holographic kits are available for such outreach programs. Thanks to this kit, a high school student club gets qualified to the national French competition “Physics Olympiads”. They produced several live hologram in presence of a jury. An inexpensive version for massive outreach is under consideration.

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