Magneto-optical imaging technique for hostile environments: The ghost imaging approach

Original
Magneto-optical imaging technique for hostile environments: The ghost imaging approach / Meda, Alice; Caprile, A.; Avella, Alessio; RUO BERCHERA, Ivano; Degiovanni, IVO PIETRO; Magni, Alessandro; Genovese, Marco. - In: APPLIED PHYSICS LETTERS. - ISSN 0003-6951. - 106:26(2015). [10.1063/1.4923336]

Availability:
This version is available at: 11696/30238 since: 2021-04-29T23:21:27Z

Publisher:
AIP

Published
DOI:10.1063/1.4923336

Terms of use:
Visibile a tutti
This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)
Magneto-optical imaging technique for hostile environments: The ghost imaging approach

Cite as: Appl. Phys. Lett. 106, 262405 (2015); https://doi.org/10.1063/1.4923336
Submitted: 12 May 2015 . Accepted: 19 June 2015 . Published Online: 30 June 2015

A. Meda, A. Caprile, A. Avella, I. Ruo Berchera, I. P. Degiovanni, A. Magni, and M. Genovese

ARTICLES YOU MAY BE INTERESTED IN

Magneto-optical imaging and analysis of magnetic field micro-distributions with the aid of biased indicator films
Journal of Applied Physics 120, 174502 (2016); https://doi.org/10.1063/1.4966225

Compressive ghost imaging
Applied Physics Letters 95, 131110 (2009); https://doi.org/10.1063/1.3238296

Turbulence-free ghost imaging
Magneto-optical imaging technique for hostile environments: The ghost imaging approach

A. Meda, A. Capriole, A. Avella, I. Ruò Berchera, I. P. Degiovanni, A. Magni, and M. Genovese
INRIM, Strada delle Cacce 91, I-10135 Torino, Italy

(Received 12 May 2015; accepted 19 June 2015; published online 30 June 2015)

In this paper, we develop an approach to magneto optical imaging (MOI), applying a ghost imaging (GI) protocol to perform Faraday microscopy. MOI is of the utmost importance for the investigation of magnetic properties of material samples, through Weiss domains shape, dimension and dynamics analysis. Nevertheless, in some extreme conditions such as cryogenic temperatures or high magnetic field applications, there exists a lack of domain images due to the difficulty in creating an efficient imaging system in such environments. Here, we present an innovative MOI technique that separates the imaging optical path from the one illuminating the object. The technique is based on thermal light GI and exploits correlations between light beams to retrieve the image of magnetic domains. As a proof of principle, the proposed technique is applied to the Faraday magneto-optical observation of the remanence domain structure of an yttrium iron garnet sample. © 2015 AIP Publishing LLC [http://dx.doi.org/10.1063/1.4923336]
interact with the sample and is sent to a spatial resolving detector (CCD camera). The technique retrieves the image of the DS exploiting correlations\(^{21-23}\) between the output of the bucket detector with each pixel of the CCD. This setup paves the way to realize MOI in extremely high magnetic fields, in window-less cryostats or whenever the accessible volume in the proximity of the sample is limited.

Thermal GI (Figure 1) requires a couple of spatially incoherent, locally correlated thermal beams,\(^{24,25}\) dubbed here as \(a\)-beam and \(b\)-beam, generally obtained by splitting a single pseudo-thermal beam through a beam splitter. In the two respective transverse planes, ideally divided in discrete resolution cells (each one larger than a “spatial coherence area”) of coordinate \(x_i\) \((i = a, b)\), the two beams present thermal intensity fluctuation statistically independent cell-by-cell

\[
\langle \delta n_k^2 \rangle = \langle n_k \rangle \left( 1 + \frac{\langle n_k \rangle}{M} \right) \approx \frac{\langle n_k \rangle^2}{M}, \tag{1}
\]

where \(\langle n_k \rangle\) and \(M\) represent the mean number of photons and the number of independent spatio-temporal modes collected within a cell during the acquisition time, respectively. \(\delta n_k = n_k - \langle n_k \rangle\) is the photon number fluctuation. The last approximation in Eq. (1), valid when \(\langle n_k \rangle / M \gg 1\), is fulfilled in typical experimental configurations. The mean photon number is conveniently expressed as

\[
\langle n_k \rangle = T_i (x_i) \lambda, \quad i = a, b, \tag{2}
\]

where \(\lambda\) is the mean number of photons impinging on the resolution cell while \(T_i (x_i)\) represents the overall locally defined transmission/detection efficiency of the channels. In GI \(a\)-beam first interacts with the object with a structured transmission profile \(\sim T_a (x_a)\), then is detected as a whole by the bucket detector, i.e., a detector without spatial resolution, whose output signal is \(N_a = \sum_k n_k\) (the sum extends over a defined number of resolution cells). The \(b\)-beam is detected by a spatially resolving detector at the correlated transverse plane, like a 2D-pixels array. The output signal from each pixel in the position \(x_b\) is denoted by \(n_{k_b}\). The point-by-point spatial correlation that emerges from the splitting of the intensity fluctuation can be expressed in terms of the covariance of the detected photon number as

\[
\langle \delta n_{k_b} \delta n_{k_b} \rangle = \frac{\langle n_{k_b} \rangle^2}{M} \delta_{k_a, k_b} = \frac{T_b T_a (x_a)}{M} \delta_{k_a, k_b}, \tag{3}
\]

where we have considered a uniform transmission-detection efficiency in the channel \(b\), i.e., \(T_b (x_b) = T_b\). Therefore, the covariance of a single pixel in \(x_b\) with the signal from the bucket detector in channel \(a\) turns out to be

\[
\langle \delta N_a \delta n_{k_b} \rangle = \sum_{x_a} \langle \delta n_{k_b} \delta n_{k_b} \rangle = \frac{T_b T_a (x_a)}{M}, \tag{4}
\]

which permits to reconstruct on channel \(b\) the transmission profile of the object interacting with beam \(a\). This is the essence of the GI technique. Equations (3) and (4) show how GI reconstruction emerges point-by-point as a correlation of pairs of resolution cells immersed in a large number of uncorrelated contributions. Thus, the statistical ensemble (namely, the number of acquired photons \(n_{k_b}\) and of values \(N_a\) should be “large enough” to allow the emergence of such correlation from the uncorrelated contribution; this increases the total duration of the experiment. Obviously, it is of utmost practical importance to quantify what does “large enough” mean for a specific GI application. As usual, the theoretical mean values are estimated by an arithmetic average of \(K\) samples from the same population, i.e., \(\langle X \rangle - E[X] = 1 / K \sum_{x=0}^{K} X_i\). In particular, the covariance in Eq. (4) is estimated by the statistical quantity \(C_{n_b} = E[(N_a - E[N_a])(n_{k_b} - E[n_{k_b}])]\). As expected, its value converges to the theoretical one

\[
\langle C_{x_b} \rangle \approx \langle \delta N_a \delta n_{k_b} \rangle, \tag{5}
\]

with fluctuations around the mean value of \((K \gg 1)\)

\[
\langle \delta (C_{x_b}) \rangle \approx K^{-1} \langle \delta (N_a) \delta (n_{k_b}) \rangle - \langle \delta (N) \delta (n_{k_b}) \rangle, \tag{6}
\]

The approximation in the second line of Eq. (6) holds since almost all the light collected by the bucket detector is uncorrelated with the pixel of the spatially resolving detector. As expected, the fluctuation scales towards zero when increasing the sample size \(K\). Let us consider now an object defined by two regions \(S_{a,j}\) \((j = +, -)\) characterized by two different transmittances \(T_{a,j}\) for \(x_a \in S_{a,j}\). On channel \(b\), we can identify two regions \(S_{b,j}\), each one locally correlated with the corresponding \(S_{a,j}\). The signal-to-noise ratio (SNR) (sometimes referred to as “contrast-to-noise ratio” in GI literature\(^{16,26-28}\)) defined as

\[
SNR = \frac{|\langle C_+ - C_- \rangle|}{\sqrt{\langle (\delta C_+)^2 \rangle + \langle (\delta C_-)^2 \rangle}}, \tag{7}
\]

should be larger than 1. In fact, by using Eq. (5) with the substitution of Eq. (4), one gets \(\langle C_j \rangle = T_b T_a \gamma^2 / M\). In the same way, the result in Eq. (6) with the substitution of Eqs. (1) and (2) returns the evaluation of each noise component at the

---

**FIG. 1.** Thermal Ghost imaging schematic representation: Two correlated beams, \(a\)-beam and \(b\)-beam, are generated by sending an incoherent beam through a 50% beam splitter (BS). Then, beams are sent to two distinct optical path: one containing the sample to be imaged and a bucket detector, and the other one containing a spatial resolving detector. The image of the sample is retrieved correlating the output of the two detectors.
denominator of the SNR as \( \langle (\delta C)^2 \rangle \approx K^{-1} T_{a,r} R_{b} \frac{x^{2}}{2\pi}, \) leading to
\[
SNR \approx \sqrt{K} \frac{|T_{a,0} - T_{a,-}|}{\sqrt{T_{a,0}^{2} + R_{+} + T_{a,-}^{2} + R_{-}}}. \tag{8}
\]

SNR is only dependent on the size of the statistical sample \( K, \) on the transmittance of the two regions \( T_{a,r} \) and on the number of resolution cells \( R_{b} \) respectively transmitted through them. In particular, in the magneto-optical application presented in this work, we have roughly \( R_{+} = R_{-} = R. \) In this case, it is easy to show that the SNR is maximized where one of the transmittances is null, reaching the optimal value \( SNR = \sqrt{K/R}. \)

The experimental setup of our magneto-optical GI experiment is depicted in Figure 2(a). The two locally correlated thermal beams, \( a\)-beam and \( b\)-beam, are obtained by means of a single pseudo-thermal beam divided by a 50-50 beam splitter. Polarized pseudo-thermal statistics light is engineered by sending coherent light pulses, such as a polarized pulsed laser beam, on a scattering medium with random scattering centers distribution, in order to obtain a speckle pattern with (pseudo) thermal intensity fluctuations. In our case, the coherent source is the second harmonic of a Q-switched Nd-YAG laser (532 nm), with pulse duration of 10 ns and repetition rate of 12.4 Hz. A spatial filter removes Q-switched Nd-YAG laser (532 nm), with pulse duration of the reconstructed image. The diameter of the speckles is evaluated as the full width at half maximum (FWHM) of the auto-correlation coefficient estimated as
\[
c(\xi) = \sum_{x_{b}} \frac{\delta n_{x_{b}} \delta n_{x_{b}+\xi}}{\sqrt{[\delta n_{x_{b}}]^{2} [\delta n_{x_{b}+\xi}]^{2}}}, \tag{9}
\]
where \( \xi \) is the two-dimensional shift of the selected region with respect to itself and \( x_{b} \) is the vector position of the pixel of the region \( b \) (see Figure 2(b)). In order to enhance the resolution, the speckle dimension was reduced by increasing the diameter of the collimated coherent source impinging on the Arecchi’s disk (see Figure 2(b)). Also, a microscope with lenses \( LM (f_{M} = 100 \text{ nm}) \) able to further reduce the speckle diameter with a magnification factor \( M = 0.2 \) was constructed. In this way the number of speckles on the sample was increased. The setup finally provides a spatial resolution of 24 \( \mu \text{m} \) at the plane of the object, largely sufficient to observe the magnetic domains of our sample.

The ghost image is reconstructed evaluating the experimental covariance \( C(x_{b}) \) averaging on the total number of frames \( K \) acquired by the CCD. We set polarizer \( P_{2} \) angle, minimizing transmittance \( T_{-}. \) In this way, we are able to get as close as possible to the ideal condition for the SNR, as discussed after Eq. (8). We finally set \( T_{b} \) with a polarizer \( PR \) in order to avoid saturation of the CCD sensor; anyway, this has no effect on the image quality (see Eq. (8)). In Figure 3, we compare GI of the Weiss domains with traditional Faraday imaging (TFI); for the chosen angle of the polarizer \( P_{2} \), we observe the intensity distribution \( n_{x} \) on the CCD area illuminated by \( a\)-beam, before summing pixels values for the bucket detector. The images of the magnetic domains of our sample obtained with GI technique (a) and with TFI (b), averaging over \( K = 46904 \) frames, include a \( (400 \times 560) \mu \text{m}^{2} \) area.

**FIG. 2.** (a) The magneto-optical GI experimental setup for Faraday microscopy of magnetic domains. In the scheme \( BS = 50-50 \) beam splitter, \( PR, P_{1}, \) and \( P_{2} \) are polarizers; \( L, LM, \) and \( LI \) are lenses of focal length \( f = 100 \text{ mm}, f_{M} = 100 \text{ mm}, \) and \( f_{I} = 75 \text{ mm}, \) respectively. (b) The auto-correlation measurement for evaluating the coherence area, before and after the microscope with magnification factor \( M = 0.2. \)
characterized by equally distributed transmittances, such that \( R_\pm = R_\mp = R \). Each pixel of the ghost image corresponds to the value of the correlation \( C_{x_\alpha} \) between \( N_a \) and the \( i \)-th pixel measurement \( n_{x_i} \). Weiss domains shape and position are evident in GI reconstruction, showing a good agreement with TFI. Differences between the two images are mostly related to a reduction of the resolution in GI. In TFI, the resolution of the image corresponds to the physical pixel dimension (8 \( \mu \)m), while for GI, we evaluated \( FWHM_{e+} \approx 3 \) pixels. Figure 4 shows the SNR of the ghost image as a function of the number of speckles \( R \) collected in areas with transmittance \( T_{a,+,} \), showing a clear agreement with the theoretical prediction.

Red line refers to a theoretical model of SNR similar to Eq. (8), but considering also a background contribution. In fact, in our case, since we estimate \( T_{a,+,} = 0.028 \), \( T_{a,-} = 0.011 \), and our pseudo-thermal light with \( M = 1 \) provides a number of photons of \( \lambda = 1210 \), the detected mean intensities are quite low: \( \bar{n}_{x_i} = 34 \) for \( x_i \in S_{a,+,} \) and \( \bar{n}_{x_i} = 13 \) for \( x_i \in S_{a,-}, \) Therefore, background variance contribution \( (V_{\text{back}} = 151) \) is not negligible in GI reconstruction.

In this paper, we proposed the application of the GI technique to magneto-optical Faraday (or Kerr) microscopy. GI is a well established imaging technique in the realm of quantum optics that allows retrieving the image of an object from an optical beam it has never interacted with. This is achieved by exploiting the correlation with its conjugated beam interacting with the object and observed with a bucket detector. Due to its flexibility, this technique appears particularly promising if magnetic domains imaging has to be performed in hostile environments (very high magnetic field, sub-K regime, limited optical access to the sample), where the possibility of collecting the light after the interaction with the sample in a minimal amount of space, even without spatial resolution, e.g., by means of a single optical fiber, allows to overcome the limitations of the experimental setup.

To prove the validity of this technique in the field of MOI, we performed a first proof-of-principle experiment exploiting the Faraday effect for imaging the domains of a YIG sample. The technique is extremely flexible, and both Kerr or Faraday configurations can be exploited. We achieved a resolution of 24 \( \mu \)m by means of a purpose developed microscope, but, with a proper design, the resolution of the ghost image can be increased at the level of traditional imaging. Our results demonstrate that this technique is able to provide high quality images of magnetic domains. In future, a system devoted to GI of magnetic domains to be used in hostile environments will be developed. This will be based on the configuration known as “computational-ghost-imaging” \(^{34,35} \) using a fibre-bundle to bring the multi-speckle-like light on the object, and a pigtailed photodiode with a multimode fiber as the bucket detector.

This work has received funding from EU-FP7 BRISQ Project, JRP EXLO2-SIQUTE Project (on the basis of Decision No. 912/2009/EC), from MIUR (FIRB “LiCHIS”-RBFR10YQ3H and PRIN “DyNanoMag”) and Progetto Premiale “Oltre i limiti classici di misura”). We thank Dr. Marco Coisson (INRIM) for useful discussions.