SAND2008-5989C

Doppler Electron Holography for Nanoscale Dynamics

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ABSTRACT

The idea of holography, originally invented by Dennis Gabor to improve the resolution of electron microscopes, has been mainly exploited using photons rather than electrons. Since that time, the vast improvement of electron optics has made the original idea of improving resolution moot; however, this does not mean that electron holography is not used. Researchers such as Möllenstedt, Lichte and Tonomura have used field emission sources to make *static* nanoscale measurements of surface height, and electric and magnetic fields. As nano-science progresses, expanding the understanding of material behavior from static to dynamic events is important. I propose to bring the holography story full circle by taking the idea of a Doppler laser vibrometer from the optical realm, and creating a Doppler electron interferometer. I will discuss the theoretical and practical considerations for creating this nano-dynamic measurement device, capable of measuring time varying electric and magnetic fields as well as object motion. The theoretical and practical considerations of creating a Doppler electron velocimeter will be discussed.

Keywords: Nano, Velocimetry, Doppler, electron holography

1. INTRODUCTION

In honor of Gabor's great contribution to measurements, and as this is a document on electron holography, it only seems appropriate to include a little historical context. In 1947 Gabor was working on the newly invented electron microscope, which had the nascent capability of great resolution due to the extremely short wavelength of light; with the glaring, and seemingly insurmountable problem of lens distortions, which drastically lowered the practical resolving power of the system. During this time, a "solution dawned" on Gabor, a solution which was ultimately to become the foundation for holography and interferometry [1]. At the time of Gabor's breakthrough, both electron and photon holography were rather impractical due to the lack of coherent sources. This delayed the application of holography in both electrons and photons until the availability of the laser in the 1960's. The elimination of the aberrations that prompted the idea of holography has been the single-minded pursuit of electron microscope manufacturers. This has lead to machines of such optical quality and refinement that imaging of atoms, the original dream of Gabor, is now realized without the need to resort to holography. These same improvements that have made holography generally superfluous for image distortion correction, have also led to the ability to create electron holography systems with the addition of one more component: the Möllenstedt-Düker biprism. The biprism was first shown in 1954 and then later published in 1955 [2-3] is the basis of nearly all practical electron interferometers in use today. As the name implies, it works by spatially splitting the beam, and then by means of an electric potential, bends the beams back together as illustrated in Figure 1. This creates two virtual and coherent sources, S_1 and S_2, which interfere in the cross-hatched area to create a fringe pattern. By placing an object in the path of one of the virtual sources (for example S_2) a phase change can be effected in one of the beams and then detected as a deviation in the fringes in the final image. A few important points, to be discussed in greater detail later, are that the beam splitter is spatial rather than the more common amplitude version used in holography and interferometry and that this is imaging at great magnification reduces the beam current and increases the exposure times required to image the fringes.

A repercussion of this single-minded pursuit of resolving power in electron microscopes has lead to ignoring the possible power of using single point measurements for dynamic purposes. Really, it has only been in the last few years that researchers have begun modifying systems to do true single point dynamic measurements [Reference from Jianyu]. As these papers indicate, there are important materials and physics experiments that can be conducted with a working dynamic electron microscope. Some work is ongoing in this area, namely in the ultra-

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fast TEM work, where the images are strobed using femto-second lasers to freeze the information. The Doppler electron velocimeter is different in that it is to work at intermediate rates, between the femto-second time scales of the ultra-fast systems and the purely static images of traditional electron microscopes. These dynamic measurements will become ever more important as research into modeling and designing nano-materials is pursued.

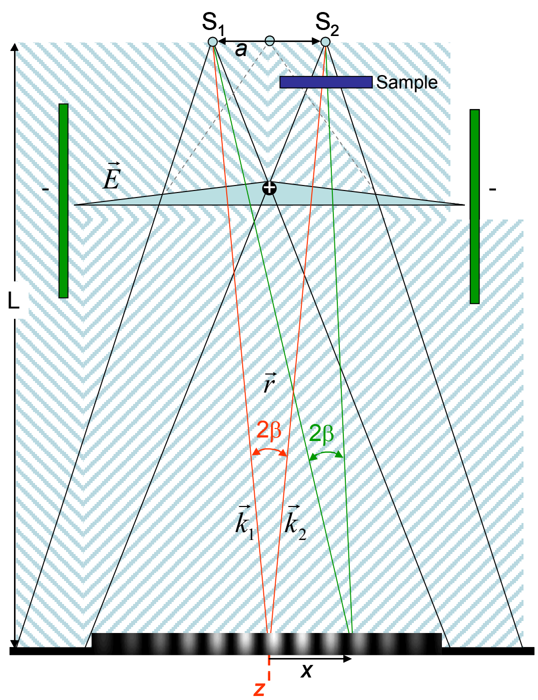

Figure 1. Schematic of the Möllenstedt biprism.

The theoretical background for the DEV has already been established [4]; some practical considerations to determine its feasibility have also been broached [5]. This paper will look at a possible electron interferometer arrangement that may hold the key to creating a functioning and useful DEV. This configuration has to my knowledge never been attempted for making interferometric measurements, particularly dynamic measurements in an electron microscope. The concept is a modified version of a successfully contrived electron diffraction with biprism interferometer successfully demonstrated by a number of researchers [6-7]. We have approached this topic from the optical realm, where the analog of this system is a Linnik microscope [8]. This paper will seek to elucidate the optical analog and why various arrangements of the Linnik microscope may be a good way to overcome the two largest hurdles to a working instrument, beam current and its closely related cousin coherence.

An analogous setup was used by Möllenstedt and Lichte [9] in the 1970's to first show a proof-of-concept Doppler shift of electrons. Their experimental setup was basically a Michelson interferometer using two biprisms: one to split the beam and another to recombine the beams to create a fringe pattern similar to that seen above. The sample was then rotated, causing the fringes to move. The Doppler frequency in this experiment was on the order of 1 Hz, orders of magnitude too small for practical dynamic measurements. It is an important experiment however, in showing that electrons indeed do Doppler shift and behave exactly as their boson brothers the photons. In order to increase the measured Doppler frequencies, the fringes will need to form more quickly. That is, a greater current will be required at the detector. There is still some question as to how high a Doppler shift can be successfully measured before a loss of coherence occurs. General thinking is that the energy shift (equivalently the Doppler shift) must be less than the spread of the beam energies [10]. Typically beam energy spreads are on the order of fractions of an electron volt. The energy shift shown in Lichte's experiment was on the order of $4e^{-15}$ eV. The energy shift for a 1 MHz Doppler shifted beam is $4e^{-9}$ eV—well within the energy spread of even a well-filtered electron source, so interference should still occur. I say "should" because no one has attempted Doppler measurements since these first extremely low frequency experiments. That interference should occur is probably not the largest hurdle; having the fringes build up fast enough to be measured at 1MHz is probably the larger hurdle.

2. THE LINNIK MICROSCOPE

2.1. Introduction to the Linnik microscope

The Linnik microscope is a well known interferometric arrangement that allows the use of a narrow band, yet spatially incoherent source to be used for interference experiments [8]. This arrangement, seen in Figure 2 is much like a Michelson interferometer and as such is ideally arranged to measure out-of-plane motions.

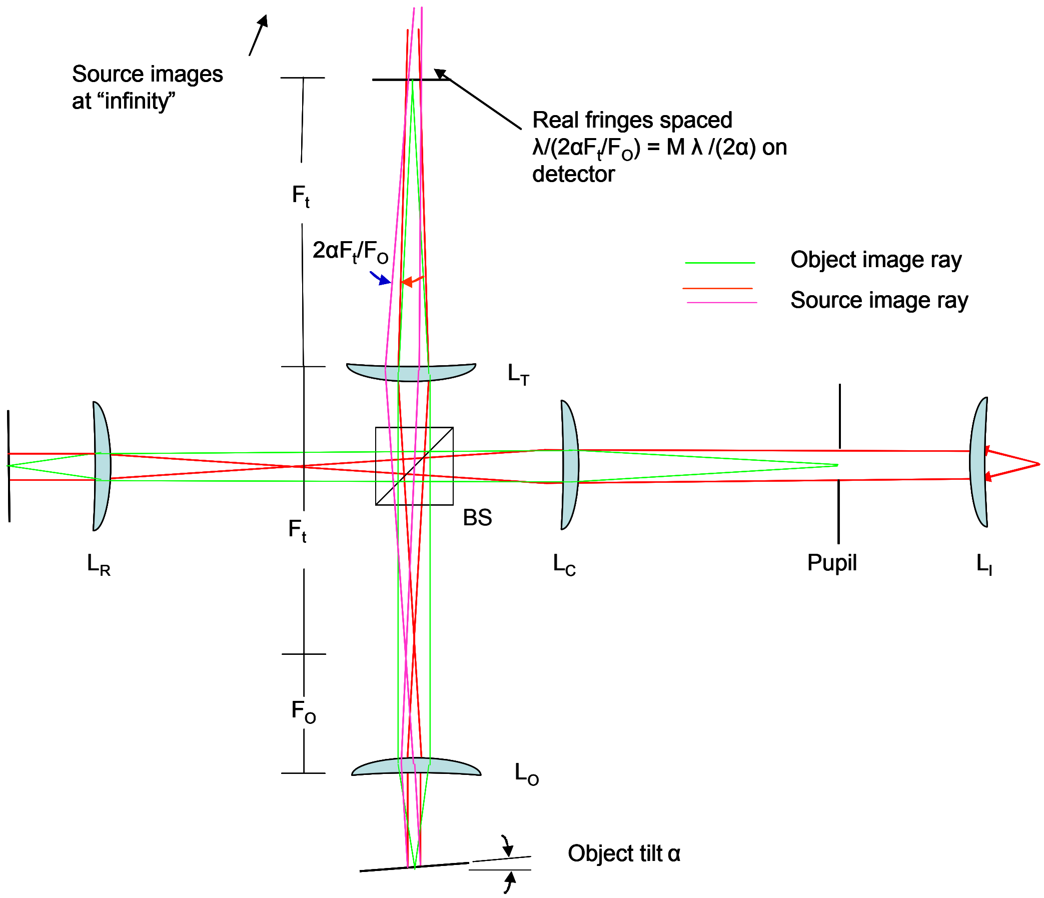

Figure 2. Point source ray diagram of Linnik Microscope

In the traditional setup, the microscope is arranged with a light source collimated by lens L_I. The illumination is then split by an amplitude splitting beam splitter with a reference and object leg with carefully matched path lengths. The matching of the path lengths is important here because the source, a green LED in our experiment, has a short coherence length, typically on the order of tens of microns. This is fairly easily accomplished experimentally by exactly matching the optical paths and components in the two legs. In our experiments, this was done by having lenses L_O and L_R be identical Mitutoyo infinity corrected microscope objectives. As previously mentioned, the light is collimated by the first lens and then imaged at infinity on the object, a small moving mirror, and a reference mirror. The light is then recombined at the beam splitter and magnified onto a CCD camera via a simple tube lens. When the system is aligned and the path lengths are matched, high contrast fringes can be produced as shown in Figure 3. If the object moves out-of-plane, the fringes will move back and forth depending on the direction of motion. If a single point detector is put into the area of a bright fringe, a Doppler single can then be measured for this simple experiment.

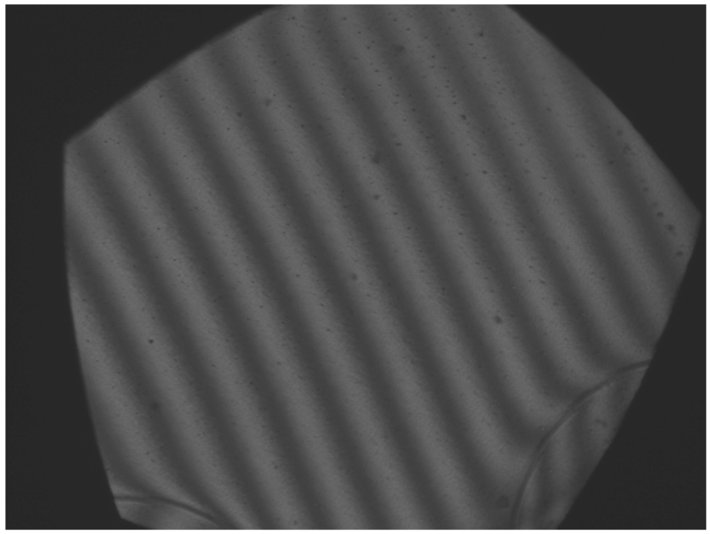

Figure 3. Collimated LED looking at a small mirror. A slight tilt is added to the object to create the fringes. Field-of-view is approximately 330 μm.

As previously mentioned, increasing beam current is one of the hurdles to detecting fast moving fringes. On this topic, note that much of the energy for the Michelson interferometer is wasted, because it is spread out over the entire viewing area. What would happen if all of the energy were focused on a single spot on the object, and then refocused on a single detector: would a higher signal be available at the detector?

2.2. Current improvements via imaging the source

With this goal in mind, the Linnik microscope was modified from a collimated source to a source imaged into the pupil and then imaged onto the object and reference mirrors. The imaged source was then recombined at the detector. A schematic of this arrangement is shown in Figure 3. Three experiments were conducted with the results shown in Table 1. The first case used a bare LED in the illumination aperture and yielded a Doppler signal of 7 mV. The traditional collimated arrangement shows an improvement in Doppler signal to 31 mV. Finally the imaged LED, where all of the source energy is collected and imaged on the object and reference indeed gives a gain in the peak to peak Doppler signal level 54-100 mV.

Table 1. Doppler signal level for different Linnik configurations.

Configuration	Mean mV	Doppler p-p mV
Bare LED	-4	7
LED collimated via single objective	-35	31
LED imaged via 2 lenses (Critical illumination)	-211	54 to 100

This particular arrangement, related to what is called Electron Beam Diffracted Interferometry (EBDI), with an amplitude splitting BS and a recombining biprism BS has been shown to be successful in the literature [6-7]. The arrangement has been successfully demonstrated in a Hitachi HF-2000 electron microscope, which is a commercially available system especially optimized for electron holography. The typically arrangement has the electron beam impinging on a crystal after traversing the first objective lens—the crystal acts as an amplitude splitting beamsplitter. The diffracted beams travel through the microscope to the biprism, where the voltage field is set to deflect the beams at the opposite angle from the crystal diffraction to overlap them. Herring specifically mentions the possibility of using this arrangement with a spatially incoherent extended source, for the reasons already outlined in this paper.

2.3. Single point Linnik Doppler measurements

To mimic the wave-front splitting function of the electron biprism, a wave-front splitting mirror was used, rather than the amplitude splitting mirror used in the previous experiments as illustrated in Figure 4. This was accomplished via a half-silvered cube as shown in Figure 5. A laser rather than a diode was used in this arrangement to simplify any temporal coherence questions, and the laser spot was focused into the field stop. With this arrangement, almost no Doppler signal resulted. This is because the beam splitter is a spatial filter. The logic implied in the ray diagram in Figure 4**Error! Reference source not found.** works on axis only. If you consider a simple coherent imaging system with the pupil split in half, you get the essentials of the interferometer, with the Doppler phase existing as a difference between the top and bottom halves of the pupil. But the focal spot can be considered to be the sum of the diffraction patterns from the top and bottom halves. As diagrammed in Figure 6, this can be viewed as the wide focal spot from the half aperture, upon which is superimposed a set of fringes. When the half apertures are in phase, the fringes serve to narrow the focal spot. But when they are out of phase, the fringes split the focal spot as shown in the bottom diagram, and in Figure 7. For this reason, the current electron microscope arrangement with two beam splitters, i.e. spatial beam splitters will not work. Fortunately that is not the only possible arrangement in an electron microscope. Using the amplitude splitting components in conjunction with a biprism, it may be possible to create a Mach-Zehnder interferometer that would work along the lines of the Linnik microscope. This would allow both a single point measurement and the use of an extended source.

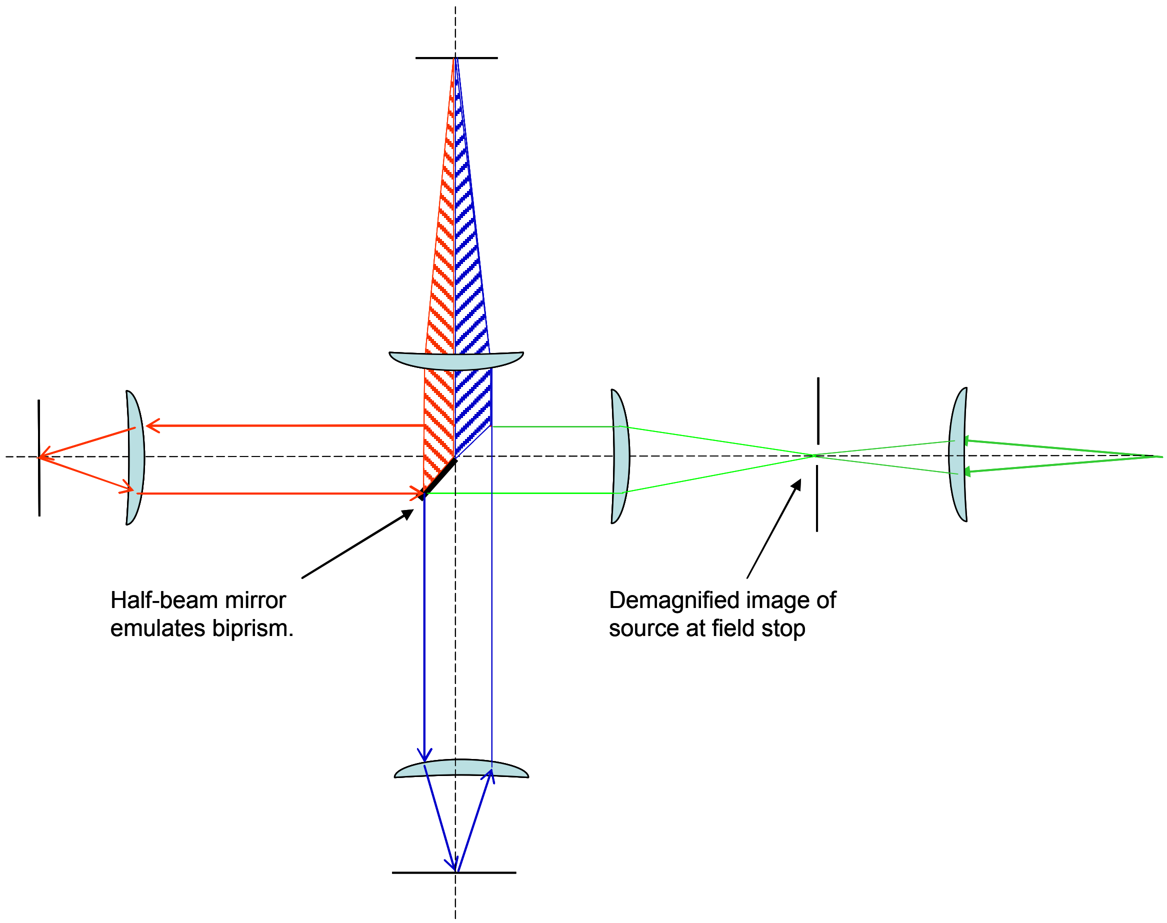

Figure 4. Linnik microscope set-up in a critical illumination case with the source imaged at the pupil and again on the reference and object legs. The wavefront splitting mirror is shown in the center.

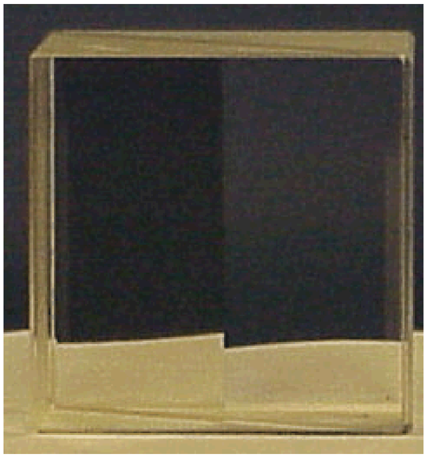

Figure 5. Photo of wave-front splitting half-silvered mirror.

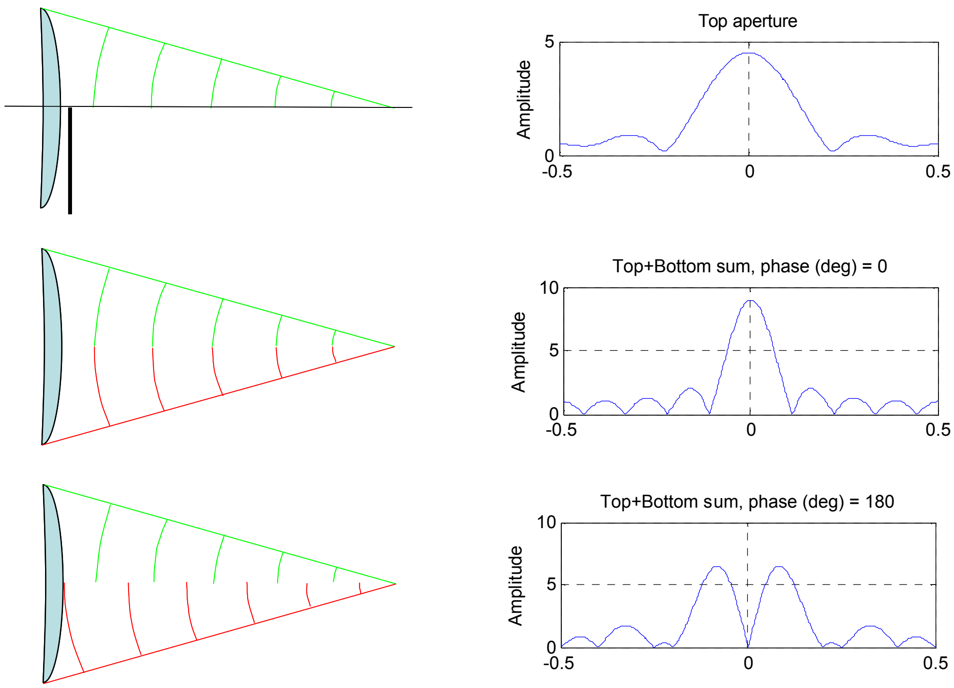

Figure 6. Diagram and resulting amplitudes at the detector for a wave-front splitting arrangement.

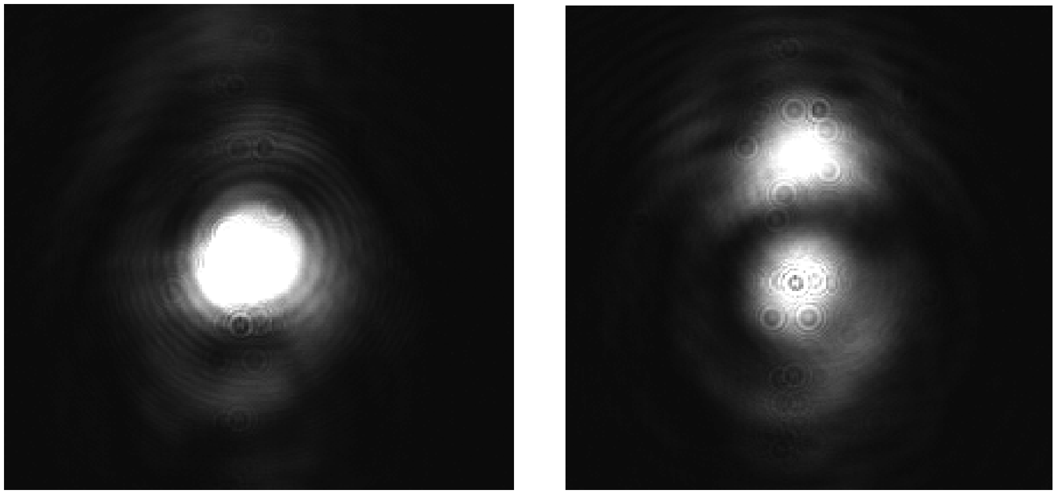

Figure 7. Focal spot of split-beam interferometer, with beams in and out of phase

3. APPLICATIONS FOR THE DOPPLER ELECTRON VELOCIMETER

3.1. Hurdles to a practical instrument

The proposed EBSD arrangement has some potential problems that are being investigated. The strength of the proposed optical arrangement is of course the increase of current at the detector, while not requiring a coherent source. However, to maintain fringe contrast system stability will likely be important. Ongoing research is being conducted to analyze the optical analog and its application in electron microscopes to answer this question. Even with this arrangement beam current may still be too limited to detect the Doppler frequencies of interest. I am currently pursuing a list of target applications that would benefit from dynamic measurements in the 1 MHz range—a value that I think is attainable with the current electron microscope equipment.

3.2. Possible applications for the Doppler electron velocimeter

One of the benefits of the DEV over the laser Doppler version is the ability to not just measure motion, but to measure electric and magnetic fields as well. Many successful experiments have already been conducted using electron holography to explore the measurement of electric and magnetic fields. Researchers have studied things as varied as the Aharanov-Bohm effect, superconducting, magnetic transition temperatures and semiconductor operation by exploiting the fact that the phase of the electron beam is sensitive to electro-magnetic fields. Some of these experiments have been attempted at video rates, and it is the belief of this researcher that if a higher rate measurement were possible, there would be a wide range of applications which could make use of it.

4. CONCLUSIONS

The DEV is a new and exciting idea for a scientific instrument, building on the strengths and varied field of application of electron microscopes in general. Past and current work has shown that the concept is theoretically possible, but the question of whether it is a practical instrument for scientific investigations is still open to debate. This paper has shown that the optical analog of the Linnik microscope, which uses a monochromatic, yet spatially incoherent source, is an intriguing possibility in helping reduce the coherence issues, which limit the available beam current for measurement. Beyond this important step, the optical analog also showed that by imaging the source, the so-called critical illumination, all of the beam energy is focused onto the detector, maximizing the Doppler current available for detection. It also showed that the biprism configuration will not work for a practical DEV. It is still an open question as to whether some of the practical aspects such as system stability, detector speed can be answered: these are topics of on-going research.

ACKNOWLEDGEMENTS

I would like to thank Tom Milster, of the University of Arizona, for many useful conversations regarding possible electron interferometer configurations. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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