

## A deeper look at the fundamentals of heterodyne detection requirements

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### INTRODUCTION

We generally accept the experimentally observed criteria for heterodyne detections that the two waves that are mixed must (i) be collinear, (ii) have matched wave fronts and (iii) cannot be orthogonally polarized. We have not found in the literature adequate physical explanations for these requirements. The purpose of this paper is to find deeper physical understanding of the coherent heterodyne detection processes that could lead to better coherent laser radar system designs<sup>1</sup>. We find that there are a number of unresolved paradoxes in classical and quantum optics regarding the definitions and understanding of the “interference” and “coherence” properties of light, which are attributed as essentially due to inherent properties of the EM waves. A deeper exploration indicates that it is the various quantum mechanical properties of the detecting material dipoles that make light detectable (visible, or measurable) to us. Accordingly, all the properties that we generally attribute to only light, are in reality manifestations of collective properties of dipole-light interactions. “Interference” and “coherence” can be better understood in terms of this mutual interaction, followed by energy absorption by the dipoles from EM wave fields, manifesting in some measurable transformation of the detecting dipoles. Light beams do not interfere by themselves<sup>2-5</sup>. The superposition effects due to light beams become manifest through the response characteristics of the detecting dipoles.

In this paper, we will show some preliminary experimental results that clearly demonstrate that the heterodyning wave fronts have quantitative degradation in signal generation as the angle between them deviates from perfect collinearity. Subsequently, we will propose a hypothesis for this behavior. We will present experimental data establishing that the so called incoherent light can be detected through heterodyne mixing as long as the pulse length contained in the “incoherent” light is longer than the response time of the detector. We will also present a correspondingly better

interpretation of two distinguishable coherence properties, temporal coherence and spectral coherence.

Our investigation provides a deeper insight into how to relax various system requirements for heterodyne detection and accordingly develop systems that are simpler, more reliable and lower in cost. Also, we believe that engineering of detector architecture by appropriately modifying dipole behavior using emerging nanotechnology to optimize heterodyne efficiency will be advantageous.

### WAVE FRONT MATCHING REQUIREMENT FOR HETERODYNING TWO OPTICAL BEAMS.

The general literature describes the key requirement for successful heterodyne detection is to have the signal and the reference beams be collinear and identical in their wave front structures. We believe that nature generally always avoids sharp discontinuities and we handle “boundary value problems” accordingly. So, we hypothesize that the collinearity and the wave front similarity of the two beams are not sharply defined and the heterodyne signal varies continuously, albeit very sharply. Here we present the preliminary results of deliberate introduction of a small variable angle between the two beams with reasonably similar wave front quality. Separate experiments where wave front quality will be varied, will be presented elsewhere.

Two multi longitudinal mode He-Ne laser beams are combined by a beam splitter before mixing (heterodyning) them on a fast detector with the help of a 75cm focal length lens. One of the beam passes through a thick glass slab before the combining beam splitter. Rotating the glass slab creates a translation of the beam on to the beam splitter making the two beams to be still focused on the detector but at an angle. We found that when the two mixing beams exceeds a few minutes of angle, the heterodyne signal vanishes.

The decrease in the strength of the signal is exponentially rapid but monotonic with the rotation of the glass plate. More quantitative results will be presented at the conference. The experiment should be repeated with very high quality aberration free optical components to determine signal sensitivity to relative wave front differences.

We believe that it is not the collinearity of the wave fronts, rather the collinearity of the Poynting vectors of the two fields that should be used in computation and measurements. The detecting dipoles that are responding to the two fields simultaneously, cannot figure out the precise directions of propagation of a light beam without being simultaneously sensitive to both the E- and B-fields. Thus the assembly of detecting "molecules" must collectively respond to the two different optical frequencies (because of QM allowed broad transition bands) simultaneously, guided by both the E- and B-fields and then transfer certain number of electrons from the valence to the conduction band which varies in time given by the difference frequency<sup>3,4</sup>.

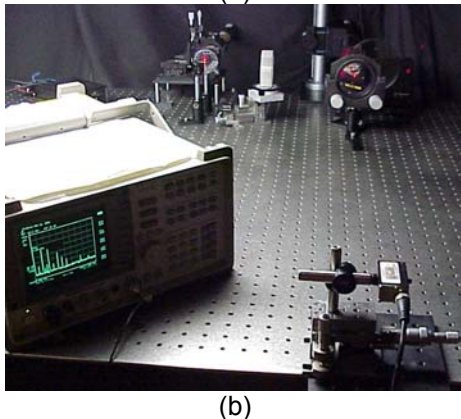
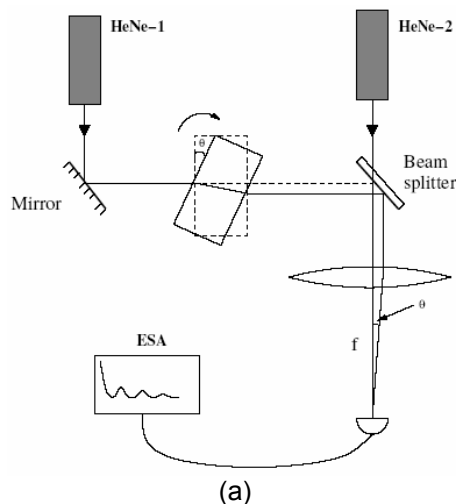


Figure 1. Experimental set up for heterodyne mixing of two He-Ne-beams with variable angles to determine the

variation of the heterodyne signal strength with angle. (a): the experimental schematic. (b): the experimental set up<sup>5</sup>.

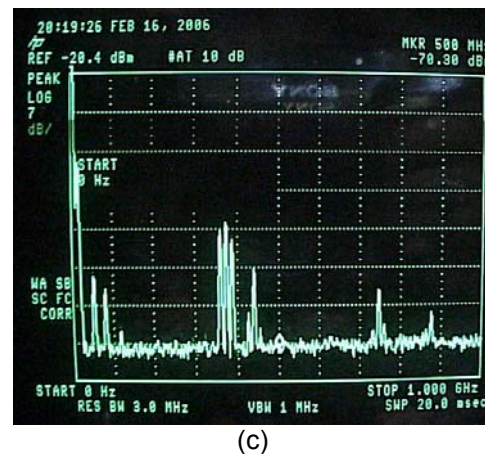
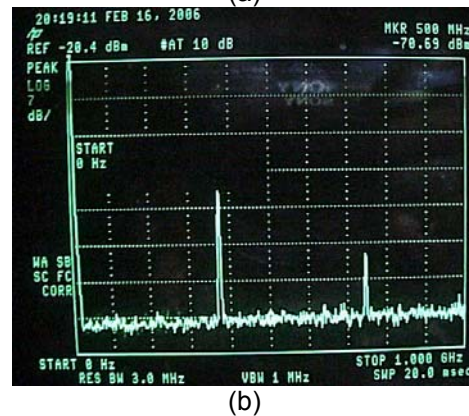
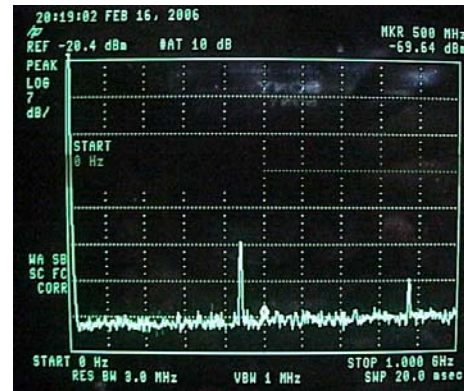


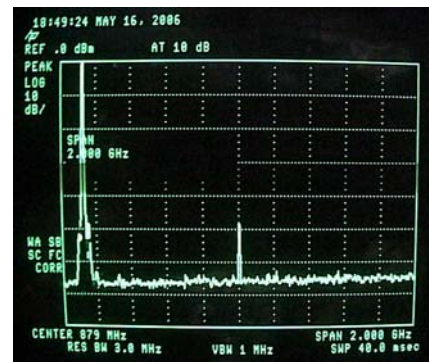
Figure 2. Heterodyne signals recorded by an electronic spectrum analyzer. Signal in (a) is for laser-1. The signal in (b) is for laser-2 and the signal in (c) is when both the lasers are simultaneously present with "perfect" collinearity. As the angle between the two laser beams is slowly increased from "zero" to a couple of degrees, the heterodyne signals rapidly diminish with exponential characteristics leaving behind simple the sum of the signal of (a) and (b).

## ORTHOGONAL POLARIZATIONS DO NOT PRODUCE HETERODYNE SIGNAL

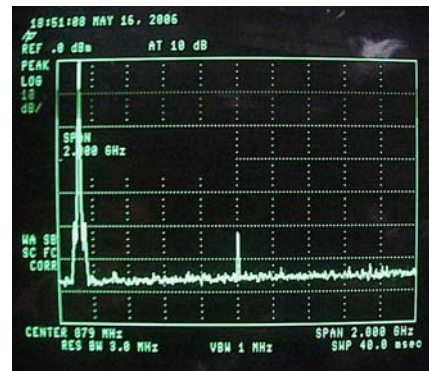
How sharply the fringe visibility goes to zero when the two superposed polarized beams intersect each other with an angle of  $90^\circ \pm \delta\theta$  between their polarization vectors? Unfortunately, we have not yet carried out this experiment for want of ultra contrast polarizing crystal. But, to underscore the roles of the detectors as the key to understand the superposition effects, we have carried out the following experiments. This set of experiments may appear trivial, but in combination with non-zero heterodyne signal for beams with small non-collinear Poynting vectors becomes relevant to underscore a common physical explanation for all superposition effects. There is no interference of light. There are only superposition effects due to light beams as manifested by the detecting dipoles when they are simultaneously exposed to all the beams and they are allowed to respond as dipoles to all the different beams simultaneously. Obviously their quantum properties constrain them from responding simultaneously to all the superposed beams giving rise to the “so called” incoherence” in the measured visibility of the fringes. Traditionally we tend to accept that different optical frequencies are incoherent to each other. In fact, experimental observations bears that out, especially for the 100+ years old Fourier transform spectroscopy invented by Michelson. Yet, with the advent of fast detector, we now routinely carry out heterodyne detection with fast, broad band photo detectors. The reason is not that light beams have mysterious properties, but because slow detectors average out the beat signal as a DC component (not zero!), giving the effect as if different optical frequencies are “incoherent”. But we know that they are not “incoherent”, otherwise we could not be detecting beat signals. Fast, broad band detectors can produce oscillatory “DC” currents at the beat signal.

Similarly, orthogonal polarized light beams are not incoherent to each other! The detecting molecules must first respond to the electric field as a dipole, which is a uni-axial mode of vibration. Once an otherwise isotropic atom or molecule starts responding to the strongest of the multiple superposed E-vectors, it is locked to that axial vibration. It cannot respond to any other weaker E-vectors if they are oscillating precisely in the orthogonal direction. The weaker E-vectors that oscillate at angles less than  $90^\circ$ , they contribute their  $\cos\theta$  components to the strongest E-vector.

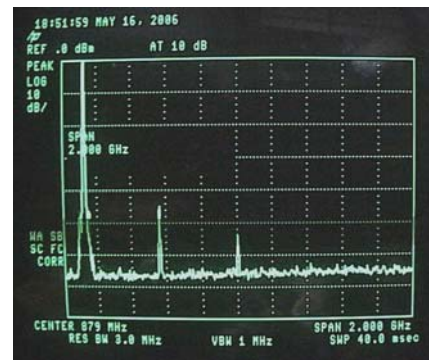
We now present some simple experimental results with He-Ne laser with mirrors sealed orthogonally right on the laser tube. Such lasers have the characteristics of running in multiple longitudinal modes where the neighboring modes are orthogonally polarized due to minute but complex gain differential<sup>6,7</sup>. The results are shown in Fig.3. A detector is fixed with a stationary polarizer and the laser tube is turned to three settings, from horizontal to vertical to  $45^\circ$  orientations. While the results are obvious, it is worth noting that we do not need to assign “coherence” properties to light beams alone – it is a joint property – field-dipole interactions constrained by the inherent quantum properties of material dipoles.



(a) Tube Horizontal



(b) Tube Vertical



(c) Tube at  $45^\circ$



Figure 3. Heterodyne signals due to a sealed-mirror He-Ne laser running dominantly in three modes where the nearest neighbors are orthogonally polarized. They mode separation is approximately 440MHz. All the signals (a), (b) and (c) are recorded with a fixed polarizer in front of the fast detector, but the laser tube is turned in “horizontal”, “vertical” and “45°” positions, respectively. Both (a) and (b) show single-line beat signal at double the mode-frequency spacing of 880MHz because the mode in between them is orthogonal to them. The signal in (c) shows two beat lines because at the 45°-setting of the laser tube, all the three laser modes sends E-vector components parallel to the polarizer axis.

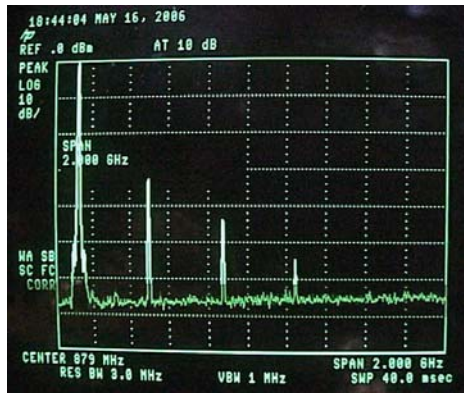


Figure 4. A He-Ne laser with Brewster windows and external cavity mirrors, have four longitudinal modes, all polarized parallel to each other. When this laser beam is sent to the detector with a fixed polarizer and the tube is rotated, the three beat signals corresponding to 1-, 2- and 3-times the mode spacing are always present with diminishing beat signal until, the tube orientation reaches the “orthogonal” state with respect to its own polarization and the polarizer in front of the detector.

To appreciate the experiments of Fig.3 better, we have recorded the beat signals from a second He-Ne laser that has Brewster windows and hence all the modes are parallel polarized. As before, this laser beam was sent to the fast detector fixed with a linear polarizer. This laser has four linearly polarized modes and hence gives three beat signal-lines with 1-, 2- and 3-times the mode spacing. As the laser tube is rotated, all the three beat lines continue to be present, but with decreasing strength until they all go to zero simultaneously when the laser polarization is orthogonal to the linear polarizer on the detector. More details of incorporating these concepts in the autocorrelation function of coherence theory will be presented at the conference<sup>8</sup>.

## CONCLUSION

We have demonstrated that the superposition effects due to light beams can be explained more

“coherently” if we accept that the effects become manifested only when the material detectors can respond simultaneously to the superposed EM field stimulations. And since material dipoles are quantum mechanical devices, the registered results will always appear to have quantum mechanical properties, irrespective of the nature of the light, whether it consists of classical divisible wave packet or quantum mechanical indivisible energy packets. Based on the finite flexibility that the Poynting vectors need not be exactly collinear for heterodyne beat signal, one can think of simplifying designs of the coherent laser radar, coherent Raman and other heterodyne systems.

## ACKNOWLEDGEMENTS

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## REFERENCES

1. T. Fujii and T. Fukuchi, (ed.), Laser Remote Sensing, Taylor and Francis, New York, 2005.
2. C. Roychoudhuri, Phys. Essays **19** (3), September 2006; “Locality of superposition principle is dictated by detection processes”.
3. C. Roychoudhuri, Katherine Creath and Al F. Kracklauer, Organizing Editors; “*The Nature of Light: What Is a Photon?*” Proc. SPIE Vol. **5866** (2005); Year of Einstein Special Conference.
4. D. Lee and C. Roychoudhuri, Optics Express **11**(8), 944-51, (2003), “Measuring properties of superposed light beams carrying different frequencies”; [<http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-8-944>]
5. C. Roychoudhuri and N. Tirfessa, Proc. SPIE Vol. **6292**-01, **Invited** (2006); “A critical look at the source characteristics used for time varying fringe interferometry”.
6. R. Ballhorn, F. Lebowsky and D. Ulrich, Appl. Opt. **14**, 2955-2959 (1975), “Beat frequency between two axial modes of a He-Ne laser with internal mirrors and its dependence on cavity Q”.
7. A. G. Laguna-Ayala and C. Roychoudhuri, Bol. Inst. Tonatzintla, Vol. **2** (2), 109-119 (1976), “States of polarization in a gas laser with internal mirrors”.
8. C. Roychoudhuri, SPIE Proceedings Vol. **6108**, paper 1E (2006), *Reality of superposition principle and autocorrelation function for short pulses*.