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INTENSITY CORRELATIONS IN OPTICAL NONLINEAR PROCESSES BY PHOTON COUNTING TECHNIQUES

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ABSTRACT

Progress is reported of current investigations of intensity correlations in two nonlinear optical phenomena: (1) optical parametric noise and (2) second harmonic generation. Details are given of the technique of two-photon delayed-coincidence counting. The result of measurements on the parametric noise field generated by a laser pumped crystal of barium sodium niobate described.

1. INTRODUCTION

Since the first observation of optical harmonics by Franken et al.[1], there has been much interest in nonlinear optical phenomena involving the parametric interaction of three or more optical waves in a nonlinear material. However, no experimental information is available which describes the statistical nature of the induced radiation fields and their correlations to different types of coherent pump sources operating under single mode, multi mode and mode-locked conditions. Such information is interesting from the viewpoint of supporting some quantum statistical treatments of nonlinear optical processes.[2] Furthermore, it characterizes correlations of the interacting radiation fields which is of interest in optical systems design incorporating quantum electronic devices.

Several techniques have been employed to measure optical field correlations from various radiation sources at two or more space-time points.[3] It is the purpose of this paper to describe a versatile approach to the measurement of correlations by photon counting and to report preliminary results of auto-correlation measurements on the tunable parametric noise emission (PN) from a laser pumped barium sodium niobate crystal ($Ba_2Na_5O_{15}$).

Measurement of the simplest type of correlation function involves sampling the optical field strength at two space-time points and forming the mean value of the product. Since this involves the product of two optical field strengths, it is a second order correlation function in classical terminology. However, optical detectors measure intensity which is the square of the optical field strength ($I\alpha|\underline{E}|^2$). So if we sample the intensity at two space-time points and form the mean value of the product of the intensities, then we get a measure of the second order intensity correlation function of the type considered in this paper. We define the normalized correlation function, or the degree of coherence by $\gamma_{1,2}(t_1,t_2)$ where

$$\gamma_{1,2}(t_1,t_2)=\frac{<:\Delta I(\underline{x}_1,\underline{t}_1)\Delta I(\underline{x}_2,t_2):>}{<:I(\underline{x}_1):><:I(\underline{x}_2):>}$$

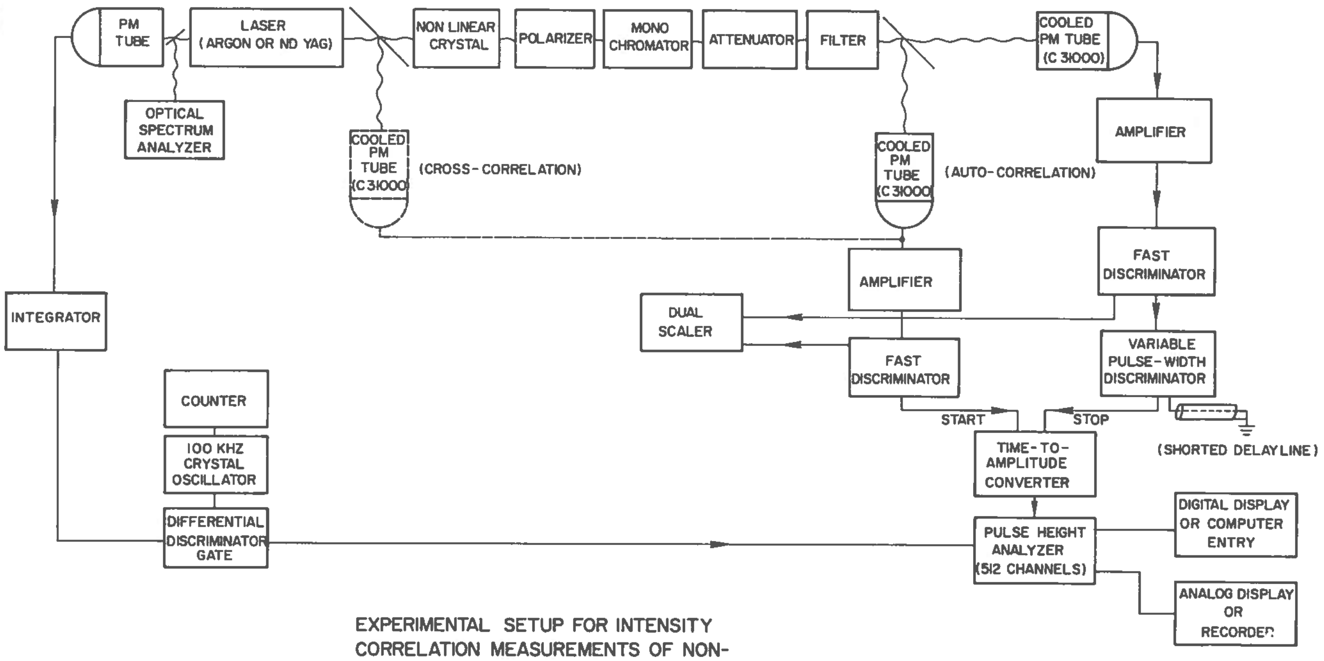
where $I(\underline{X}_1,t_1)$ and $I(\underline{X}_2,\underline{t}_2)$ are, respectively, the measured intensities at points 1 and 2 and at times t_1 and t_2. We define $\gamma_{1,2}$ as the cross correlation function. If the space points are the same, then $\gamma_{1,1}$ defines the autocorrelation function. In all cases, $0\underline{<}\gamma\underline{<}1$ where $\gamma=0$ corresponds to total incoherence and $\gamma=1$ corresponds to complete coherence. The experimental determination of correlation involves the counting of pairs of photons and measuring the probability that both photons are present at a certain pair of space points, at a certain pair of time points.

Determination of the autocorrelation function of a stationary optical field at a given space point yields a direct measure of the coherence time, and thus of the spectral purity of the optical field. Correlation times ranging from a fraction of a nanosecond to about 50 microseconds can be measured by time-to amplitude converter techniques. Interferometric measurements are often impractical, and cannot be used here due to the low intensity of the parametric noise emission.

Cross-correlations are determined when the observed space points are distinct. This is accomplished by separating the pump and induced optical fields with narrow-band pass filters and polarizers. Knowledge of the cross-correlation functions offer statistical information regarding the particular nonlinear optical process involved.

2. THE EXPERIMENT

The experimental apparatus is illustrated in Fig. 1. The essential elements are a stable, single-mode laser pump (see Fig. 2), a nonlinear crystal located in a tempera-



EXPERIMENTAL SETUP FOR INTENSITY CORRELATION MEASUREMENTS OF NON-LINEAR OPTICAL RADIATION FIELDS

Fig. 1

ture controlled oven, two photomultiplier detectors, 100MHz counting instrumentation, a time-to-pulse-height converter, a pulse-height analyzer, and suitable digital and analog readout equipment.

A parametric noise emission signal was generated at 6430Å from a phase matched $Ba_2NaNb_5O_{15}$ crystal pumped with 500mw of 4880Å single mode radiation.[4] The optimized PN signal is carefully filtered to eliminate the pump and stray radiations. This is accomplished by following the crystal with a band pass filter and polarizer (the E vector of the fluoresence signal is orthogonal to the pump). The fluoresence signal is then focused on the entrance slit of a Jarrell-Ash monochrometer which serves as a selectable narrow band (~2A) filter. The selected fluoresence signal is then split into two beams, each of which falls on the photocathode of a photomultiplier tube. The detected signal is of the order of 10^{-10} watts. With powers of this magnitude, single photon pulses, rather than analog signals, are easily measurable with counting electronics of 100MHz resolution.

Detectors used for the measurements are RCA photomultiplier tubes of the C31000 developmental series. A C31000F with an extended S20 photocathode response is used for the visible, and a C31000J with an S1 cathode response is used for wavelengths approaching the near infrared. The tubes were selected on the qualities of fast response (>300MHz single-electron pulse resosution), high current gain, and a relatively high quantum efficiency with minimum thermionic emission. Minimization of thermal electron emission from the photocathode is most important in preparation of the detectors for photon counting work. It has been necessary to cool the tubes, particularly the C31000J, with nitrogen to reduce the dark count rate to $<5\times10^2$ counts per second.

The dark-noise count rate sets a lower limit on the photon count rate necessary to achieve meaningful statistics of the observed radiation field. Also, of course, there is an upper limit on the measurable counting rate ultimately determined by the resolution of the detection system. But for our purposes, photon count rates were limited to $<10^4$ per second due to facilitating approximations in the data reduction.

Fig. 3 shows measured integral pulse-height distribution curves for both the C31000F and the C31000J operating at two different voltages. These distributions indicate the optimum combination of tube operating voltage and detection threshold set by the discriminators for photon-counting statistics.

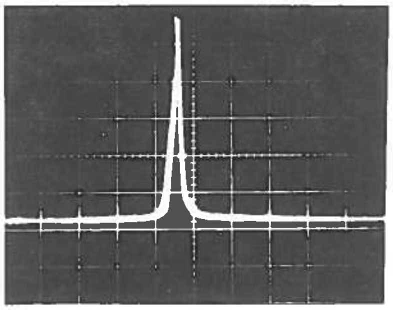


Fig. 2. Single mode frequency spectrum of argon laser operating at 4880A. (Dispersion, 100 MHz/div.)

Ideally, all photo electron pulses would be of equal amplitude, and detection would be assured with proper threshold setting. However, the pulse-heights follow a near-Poisson distribution[5] if the detector is operated correctly. Setting the threshold on a reasonably flat portion of the distribution assures the detection of most all of the pulses of single-photon orgin. If the threshold is established on a more steeply sloped portion of the distribution, then it is likely that photons grouped in times less than the detection resolution register a count, while single photons do not register a count. Therefore the distribution curves in Fig. 2 show that the tubes should be operated at 2000 volts rather than 1800 volts. Such operation also allows more freedom in setting the threshold. This is an important advantage since radio frequency pickup has been extremely difficult to shield at threshold settings less than about 2mv. In addition, the full gain capabilities of the photomultiplier tube should be utilized since it is a superior broadband amplifier compared to the subsequent external pulse amplifiers.

The desired counting rates (10^4 sec^{-1}) are adjusted by optical attenuators and not by the detection gain parameters which are optimized on the basis of the detector statistics.

The individual photoelectron pulses are amplified and then standardized by the fast discriminators. The fast rise-time discriminator pulses represent the position of photon arrivals in time. Photon arrival pulses from one detection channel are fed into the start input of the time-to-amplitude converter (TAC). Pulses from the other channel are delayed by pulse stretching and clipping, and are then fed into the stop channel of the TAC. The TAC then converts "start"-"stop" arrival time differences within a prescribed conversion range into an analog pulse height. These pulse heights are finally stored as digital information in the multichannel pulse-height analyzer (MCPHA). The delay of one detection channel with respect to the other merely allows true coincidences (zero time difference) to correspond to finite pulse-height in a linear region of the TAC-MCPHA system. Provisions are available for gating on the MCPHA only when the observed radiation field is within a selected range of intensities.

Counts in the PHA represent the probability of two-photon delayed-coincidence as a function of arrival-time delay. Qualitatively, a quasi-flat distribution represents an accidental coincidence rate while excess peaking represents photon correlations for which the correlation times can be measured.

The two-photon correlation function

$$<:\hat{I}(\underline{x},t_1)\hat{I}(\underline{x},t_1+\tau):>$$

of the optical parametric noise field was investigated. The quantity

$$<:\hat{I}(\underline{x},t_1)\hat{I}(\underline{x},t_1+\tau):>$$

denotes a product of normally ordered operators that describe the intensity of the optical field at the space-time points $\underline{x},t_1$ and $\underline{x},t_1+\tau$, and the angular brackets denote an ensemble average over all realizations of the fluoresence field.

The rate $R(\tau)$ at which conversions are stored in the MCPHA correspond to photons absorbed at the space-time points $\underline{x},t_1$ and $\underline{x},t_1+\tau$. This rate is given by[6]

$$\overline{R}(\tau)=\Delta\tau\alpha_1 cS_1\alpha_2 cS_2<:\hat{I}(\underline{x},t_1)\hat{I}(\underline{x},t_1+\tau)\times \exp[-\alpha_2 cS_2\int_{t_1-T_L}^{t_1+\tau} I(\underline{x},t'dt']\times \exp[-\alpha_1 cS_1\int_{t_1-T_W}^{t_1} I(\underline{x},t'')dt'':>\times \text{DT FACTOR} \qquad (1)$$

α_1 and α_2 are the dimensionless quantum efficiencies of the photocathodes, S_1, S_2 the effective surface areas of the photodetectors, T_W the full scale conversion range of the TAC, T_L the arbitrary delay introduced to identify true coincidences, and $\Delta\tau$ the width in microseconds per channel of the MCPHA.

If the optical field incident on the detectors has no correlated intensity fluctuations, then $R(\tau)$ reduces to

$$R(\tau)=R_1R_2\Delta\tau e^{-R_1T_W}e^{-R_2(T_L+\tau)}\times\text{DT FACTOR} \qquad (2)$$

where R_1 and R_2 are the average counting rates of the detectors. If correlated intensity fluctuations are present, $R(\tau)$ increases above the rate predicted by Eq. 2.

The normalized intensity correlation function $<:\Delta\hat{I}(\underline{x}\ ,t_1)\Delta\hat{I}(\underline{x}\ ,t_1+\tau):>/<:I(\underline{x}):>^2$ can then be extracted by the computational procedure given in Ref. 6.

The response of the counting apparatus was verified by observing the two-photon correlations of an optical field produced by a pseudo thermal source[6]. This is accomplished by focusing the light of the argon laser onto a rotating ground glass disc. Results of the measurement are

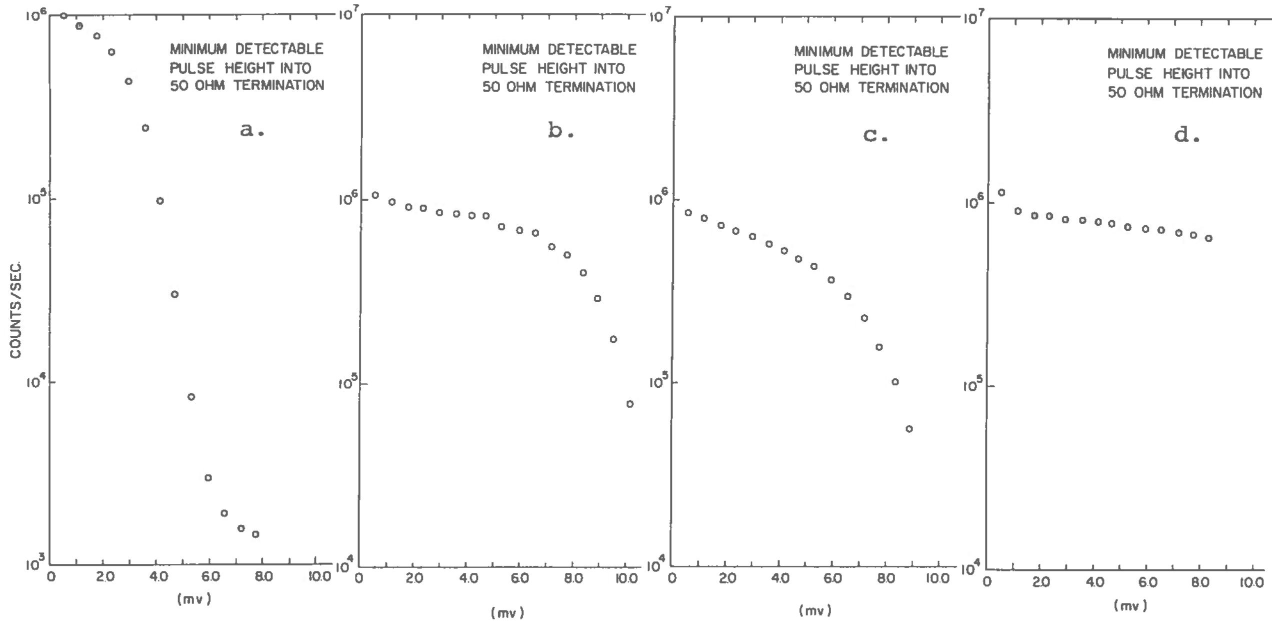


Fig. 3. Integral pulse-height distributions for superposition of dark pulses and photon pulses from an attenuated 6328Å He-Ne laser source.
(a) RCA C31000F, 1800 V, 22°C. (c) RCA C31000J, 1800 V, -63°C.
(b) RCA C31000F, 2000 V, 22°C. (d) RCA C31000J, 2000 V, -63°C.

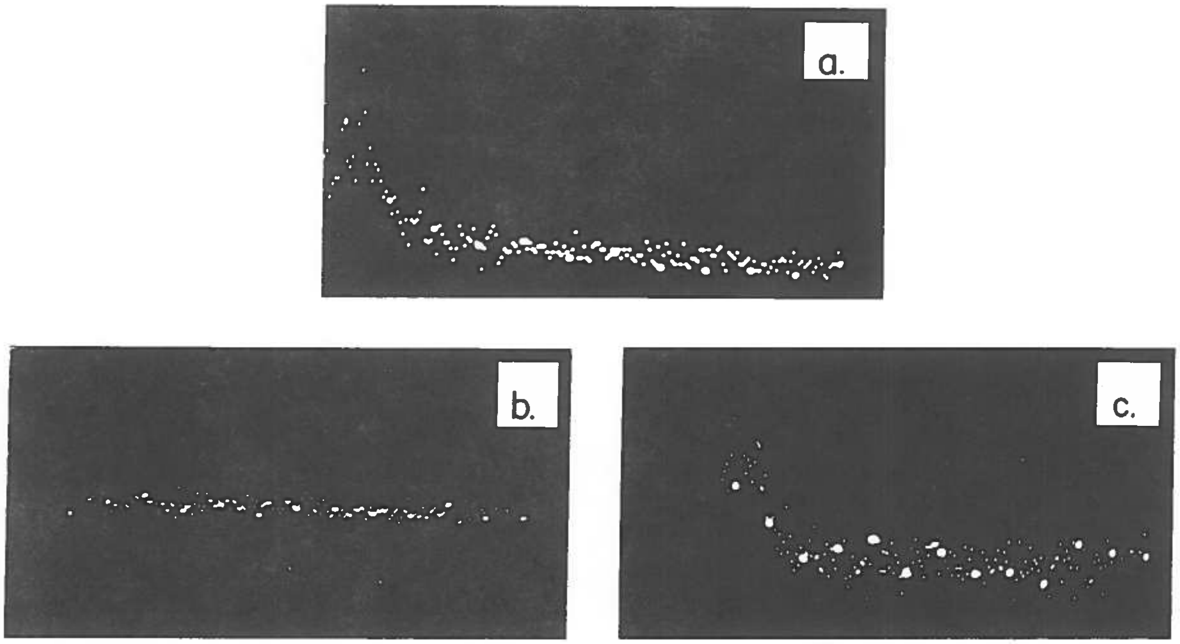


Fig. 4. Pulse height analyzer display of recorded TAC conversions.
(a) Pseudo thermal source, 0.9 nsec/channel.
(b) PN emission signal, 0.88 μsec/channel.
(c) PN emission signal, 0.322 nsec/channel.

shown in Fig. 3(a), which displays the number of counts stored in each channel of the MCPHA as a function of channel number, and hence as a function of photon arrival time difference. The observed correlations are indicated by the excess number of counts recorded in channels corresponding to τ values up to about 75 ns. The slightly exponential region of the distribution represents the number of counts expected in each channel for a field with no intensity fluctuation correlations.

3. RESULTS AND CONCLUSION

The results of auto-correlation measurements on the parametric noise field are displayed in Figs. 4(b) and 4(c). In the case of Fig. 4(b), the conversion range of the TAC was 30 μs with $\Delta\tau$=.088 μs/channel. The quasi-flat distribution indicated no measurable correlations on this scale. However, correlations of intensity fluctuations predicted in Ref. 2 become observable upon using a TAC conversion range of 100 ns, as is shown in Fig. 4(c). This indicates coherence times of a few ns for the parametric noise emission from the laser pumped $Ba_2NaNb_5O_{15}$ crystal. A significant increase in the coherence time of this radiation is to be expected upon insertion of the nonlinear crystal inside an optically resonant cavity.

4. ACKNOWLEDGMENTS

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