Observation of induced coherence in parametric down conversion experiments

Rene Stock

Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131

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Abstract

Interference experiments with signal and idler photons produced by parametric down conversion are described. When the paths of the two idler photons are superposed and aligned, coherence between the two signals is induced resulting in nonclassical interference. If the idlers are misaligned or blocked the induced interference disappears. An attempt is made to give an interpretation of this effect.

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I. INTRODUCTION

Feynman described the phenomenon of interference as containing "the only mystery" of quantum mechanics [1]. Nonclassical interference effects give key insights into the quantum nature of particle interactions. An explanation of such effects is therefore crucial for the understanding of quantum dynamics. A basic requirement for interference is coherence between the interfering quantum states [2,3]. If initially there is no coherence present in a quantum system, under certain circumstances coherence can be induced, resulting in interference. Mandel et al. have performed beautiful photon correlation experiments demonstrating induced coherence effects [4–8]. In one of these experiments which employs parametric down conversion in two nonlinear crystals, coherence is induced between the two signals photons when the paths of the idler photons are aligned. The resulting nonclassical interference results from the indistinguishability of paths of the signal photons that is induced by the alignment of the two idler beams. If the two idlers are misaligned or separated by a beam-stop, allowing "which path"-information, the interference disappears. It should be further noted that the observed interference pattern is a second order interference effect in contrast to other interference experiments that show fourth order interference in coincidence detection [9,10].

A description of the experiment is presented in the following paper. A discussion is given from the point of view of "which path"-information, which has been investigated in several interference experiments [9–14]. The experiment is also explained using QED arguments. A further interpretation is given in terms of vacuum fluctuation induced coherence.

II. CREATION OF PHOTON PAIRS IN PARAMETRIC DOWN CONVERSION

Optical parametric down conversion has long been considered an important source for squeezed states [15–19] as well as a way of creating entanglement [13,14,20–22]. In optical parametric down conversion a pump beam is incident on a nonlinear birefringent crystal, creating one or more photon pairs with a low conversion efficiency f. The state of the field can be written as Fock States in the following way,

$$|\chi\rangle = |0\rangle + f\,|1_s 1_i\rangle + f^2\,|2_s 2_i\rangle + \cdots . \tag{1}$$

n_s and n_i are the number of signal and idler photons in a given mode of the field [23]. Due to the very low conversion efficiency f of the parametric process the creation of two or more photon pairs can be neglected. For all practical purposes therefore only one pair consisting of signal and idler is of interest. The correlation time of the photon pair is on the order of $100fs$ [24]. The photon pair fulfills the usual phase matching conditions [25],

$$\begin{aligned} \omega_s + \omega_i &= \omega_p, \\ \vec{k}_s + \vec{k}_i &= \vec{k}_p. \end{aligned} \tag{2}$$

The sum of the frequencies of the created photon pair is therefore well defined by the pump laser frequency ω_p. The individual frequency spectrum is relatively broadband because there are several ways to fulfill Eq.(2). The propagation directions of the two light quanta (collinear or different directions), which reflects the phase matching relations, are determined by the orientation of the crystal. Additionally the downconversion can be categorized in terms of the polarization (parallel or orthogonal) of the photons as type I or II. In practice, in order to create a photon pair that is entangled in momentum and phase, degenerate photons are selected by several apertures and interference filters. Furthermore several ways of producing polarization entangled photon pairs have been introduced in a number of experiments using type II downconversion [13,14,20–22,25,26].

III. INDUCED COHERENCE AND INDISTINGUISHABILITY IN OPTICAL COHERENCE: THE ZOU, WANG AND MANDEL EXPERIMENT

A. Experiment

It is well known that light produced in stimulated emission is coherent with the stimulating field. It has been shown in theory and experiment [27,28] that a parametric down conversion process can also be stimulated by a strong external field. If the external field is much weaker, however, the down conversion occurs spontaneously and at random, not showing any coherence. Nevertheless it has been demonstrated by Mandel et al [4,5] that it is possible to induce coherence in down conversion without induced emission. In this experiment two nonlinear crystals NL1 and NL2 were pumped coherently (amplitude V_1 and V_2) producing two pairs of signal and idler beams via spontaneous parametric down conversion (Fig. 1). The two idlers are initially aligned and indistinguishably detected with detector D_i. The two signals are combined at detector D_s, looking for interference between the signal photons while the path difference between s_1 and s_2 is varied slightly on a timescale shorter than the coherence time τ_c. It must be noted that in this experiment the intensity of the idler beam coming from NL1 is too weak to induce any stimulated down conversion, so that any observed coherence is not due to an induced emission process. If the idlers and the signals are both aligned it is clear that the joint detection probability P_{12} shows fourth order interference. The detectors cannot distinguish between the photon pairs s_1, i_1 and s_2, i_2 and therefore fourth order interference is observed.

The detection rate of the signal photon detector D_s alone is also of interest. If the idlers are misaligned or a beamstop is placed between NL1 and NL2 no interference is observed. This result is expected, since the two signal photons should show no first order coherence. However, when the idlers are aligned, interference fringes appear showing that coherence is induced between the two signal photons. If one looks now at the “which path”-information that is present in the two cases, the appearance of the interference becomes clearer. As long as the idlers are aligned and indistinguishable one cannot tell from which crystal the detected signal photon came from. This lack of “which path”-information accounts for interference. If the two idlers are now made distinguishable by a beamstop, one can tell whether the photon originated in NL1 or NL2: If D_i also measured a photon, then the photon pair must have originated in NL2, otherwise it must have come from NL1. As long as the two idlers are now distinguishable, one has “which path”-information, therefore resulting in no interference. If, however, the two idlers are indistinguishable, in either case an idler photon is detected at D_i and the measurement is not producing any information about the path of the signal photons. First order coherence is induced between the two signal beams.

Another striking result of this experiment is that the detector D_i is not needed to actually measure the which path information. The fact that a "which path"-measurement *could* be made is sufficient to wash out the fringes. Therefore, as stated by Mandel et al. [4], "...the state or density operator reflects not only what is known but to an extent also what could be known, in principle, about the photon."

B. Photon-photon correlation from the point of view of QED

In order to gain a better insight into the Zou-Wang-Mandel experiment we replace the two nonlinear crystals by two three level atoms [19,29]: After excitation by a classical pump wave with low intensity, that is resonant with the $|c\rangle \rightarrow |a\rangle$-transition the state of the system can be written as (Fig. 2)

$$|\chi_i\rangle = \frac{1}{\sqrt{2}}\left(|a_1 c_2\rangle + |c_1 a_2\rangle\right)|0\rangle\,, \tag{3}$$

where the atom-field ground state is given by $|\chi_0\rangle = |c_1 c_2\rangle\,|0\rangle$. Once the atom is excited, it rapidly decays back to its ground state by the emission of two photons $|\gamma_i\rangle$ and $|\phi_i\rangle$, resulting in the final state

$$|\chi_f\rangle = \frac{1}{\sqrt{2}}\,|c_1 c_2\rangle\left(|\gamma_1\phi_1\rangle + |\gamma_2\phi_2\rangle\right). \tag{4}$$

We are interested in the interference that can be seen in the detection of the photons coming from the two atoms. We therefore need to calculate the first and second order correlation functions [2,3] for the state $|\chi_f\rangle$. For a detector which is sensitive to $|\phi\rangle$-photons, the field correlation is then given by

$$\begin{aligned}
G^{(1)}(\vec{r},t) &= \langle\chi_f|\,\hat{E}^{(-)}(\vec{r},t)\hat{E}^{(+)}(\vec{r},t)\,|\chi_f\rangle \\
&= \frac{1}{2}\,[\langle\phi_1|\,\hat{E}^{(-)}(\vec{r},t)\hat{E}^{(+)}(\vec{r},t)\,|\phi_1\rangle\,\langle\gamma_1|\gamma_1\rangle \\
&\quad + \langle\phi_2|\,\hat{E}^{(-)}(\vec{r},t)\hat{E}^{(+)}(\vec{r},t)\,|\phi_2\rangle\,\langle\gamma_2|\gamma_2\rangle \\
&\quad + \Big(\langle\phi_1|\,\hat{E}^{(-)}(\vec{r},t)\hat{E}^{(+)}(\vec{r},t)\,|\phi_2\rangle\,\langle\gamma_1|\gamma_2\rangle + c.c.\Big)].
\end{aligned} \tag{5}$$

Any second order interference depends on the last term in the first order correlation function, which is proportional to the inner product $\langle\gamma_1|\gamma_2\rangle$.

If we now take a look at the ZWM-experiment using this general description of a three level atom as parametric downconverter, we can identify the signal photons of section III A s_1 and s_2 with ϕ_1 and ϕ_2 and the idler photons i_1 and i_2 accordingly with γ_1 and γ_2. If the beamstop keeps the two idler photons $|\gamma_1\rangle$ and $|\gamma_2\rangle$ from overlapping, then the two photons are states of two different modes and orthogonal. The last term in Eq. (5) is then evaluated to zero.

$$\langle\gamma_1|\gamma_2\rangle = 0 \;\Rightarrow\; \text{no interference.} \tag{6}$$

If the beamstop is absent the two photons correspond to states of one mode. The last term is then unity.

$$\langle\gamma_1|\gamma_2\rangle = 1 \;\Rightarrow\; \text{interference.} \tag{7}$$

In this case first order coherence is induced and interference is observed.

Furthermore, QED also provides an explanation of the fourth order interference observed (Section III A). In the ZWM-experiment we can look for coincidence detection between the detectors D_s and D_i. We then need to calculate the second order correlation function,

$$\begin{aligned} G^{(2)}(\vec{r},t) &= \langle\chi_f|\,\hat{E}^{(-)}(\vec{r}_a,t_a)\hat{E}^{(-)}(\vec{r}_b,t_b)\hat{E}^{(+)}(\vec{r}_a,t_a)\hat{E}^{(+)}(\vec{r}_b,t_b)\,|\chi_f\rangle \\ &= \frac{1}{2}\,[\langle\gamma_1|\,\hat{E}_a^{(-)}\hat{E}_a^{(+)}\,|\gamma_1\rangle\,\langle\phi_1|\,\hat{E}_b^{(-)}\hat{E}_b^{(+)}\,|\phi_1\rangle \\ &\quad + \langle\gamma_2|\,\hat{E}_a^{(-)}\hat{E}_a^{(+)}\,|\gamma_2\rangle\,\langle\phi_2|\,\hat{E}_b^{(-)}\hat{E}_b^{(+)}\,|\phi_2\rangle \\ &\quad + \Big(\langle\gamma_1|\,\hat{E}_a^{(-)}\hat{E}_a^{(+)}\,|\gamma_2\rangle\,\langle\phi_1|\,\hat{E}_b^{(-)}\hat{E}_b^{(+)}\,|\phi_2\rangle + c.c.\Big)]. \end{aligned} \tag{8}$$

The joint detection probability always shows interference due to the non vanishing last term. The detectors cannot distinguish between the photon pairs (ϕ_1, γ_1) and (ϕ_2, γ_2), resulting in the observed fourth order interference. In summary the predictions made by QED are in complete agreement with the experimental results (section III A).

C. Theory of Vacuum-fluctuation induced coherence

The QED description of the previous section provides an appropriate theoretical framework for explaining the interference. However, the actual effect that coherence is induced between two originally independent photons is not very intuitive. The following explanation of Mandel's experiment follows the heuristic approach of Scully et al. [19,29]. It should be stressed that this approach is no substitute for a full QED analysis, but is a useful and intuitive picture for understanding the physics behind the experiment.

In this heuristic picture of vacuum fluctuations, a stochastic electromagnetic field induces an atomic transition and accounts for the random phase of the emitted radiation. For this explanation based on classical fluctuating fields the two crystals are once again replaced by two three level atoms 1 and 2. These two atoms are excited by a weak pump and emit two classical fields γ_i and ϕ_i $(i = 1, 2)$ after excitation. The state of each atom after excitation $|\chi\rangle = c_a |a\rangle + c_c |c\rangle$ is subject to perturbations by vacuum fluctuations that induce some population transfer δc_b from $|a\rangle$ to $|b\rangle$ such that

$$|\chi\rangle = c_a |a\rangle + \delta c_b |b\rangle + c_c |c\rangle \,. \tag{9}$$

The vacuum fluctuations interacting with the transition $|b\rangle$ to $|c\rangle$ are not taken into account here, as they are second order in the field.

The population δc_b has the random phase of the inducing field $\phi_{\gamma,i}$ causing the dipole formed by the levels $|a_i\rangle$ and $|b_i\rangle$ to radiate with the phase $\phi_{a,i} - \phi_{\gamma,i}$, whereas the dipole formed by $|b_i\rangle$ and $|c_i\rangle$ starts radiating with $\phi_{\gamma,i} - \phi_{c,i}$. Knowing these phases we can write out the total dipole moments that radiate the following fields,

$$E_i(\vec{r},t) = E_i^{\gamma}(\vec{r},t) + E_i^{\phi}(\vec{r},t) \tag{10}$$

$$E_i^{\gamma}(\vec{r},t) = |\mathcal{E}_i^{\gamma}(\vec{r})| \times \exp[-i\omega_{ab}t + i(\phi_{a,i} - \phi_{\gamma,i}) + ik_{\gamma,i}(\vec{r} - \vec{r}_i)] \tag{11}$$

$$E_i^{\phi}(\vec{r},t) = \left|\mathcal{E}_i^{\phi}(\vec{r})\right| \times \exp[-i\omega_{bc}t + i(\phi_{\gamma,i} - \phi_{c,i}) + ik_{\phi,i}(\vec{r} - \vec{r}_i)]. \tag{12}$$

Given the electric fields one can now calculate the classical counterpart of Glauber's first order coherence function, where the key terms are the two atom cross terms yielding

$$\begin{aligned} G^{(1)}(\vec{r},t) &= \langle E^*(\vec{r},t)E(\vec{r},t)\rangle \\ &= |\mathcal{E}_1^{\gamma}(\vec{r})\mathcal{E}_2^{\gamma}(\vec{r})|\,\langle \exp[i(\phi_{\gamma,1}-\phi_{\gamma,2})]\rangle \\ &\quad \times \exp[-i(\phi_{a,1}-\phi_{a,2}-ik_{\gamma,1}(\vec{r}-\vec{r}_1)+ik_{\gamma,2}(\vec{r}-\vec{r}_2)] + \cdots . \end{aligned} \tag{13}$$

Now we consider the two different cases in the Zou, Wang and Mandel experiment. In the case with the beamstop in the idler path the two vacuum phases of γ_1 and γ_2 are statistically independent and the averaging process will therefore lead to zero coherence.

$$\langle \exp[i(\phi_{\gamma,1}-\phi_{\gamma,2})]\rangle = 0 \;\Rightarrow\; \text{no interference.} \tag{14}$$

Therefore no interference will be observed.

If the beamstop is removed, the vacuum field stimulating the emission in atom 1 will travel to atom 2 and therefore impart the same phase to both atoms. The average in this case will then be unity, resulting in induced second order interference as observed in the experiment.

$$\langle \exp[i(\phi_{\gamma,1}-\phi_{\gamma,2})]\rangle = 1 \;\Rightarrow\; \text{interference.} \tag{15}$$

In summary. the predictions of the vacuum fluctuation logic are equivalent to the ones derived in QED. Scully et al mention though that this quantum fluctuation logic only provides the right answers under certain limitations [29]. Under certain circumstances the predictions may even contradict the QED results. Nevertheless this theory gives an intuitive physical insight into the studied experiment, showing that the induced coherence is due to the vacuum fluctuations imparting the same phase to the nonlinear processes in both crystals.

D. Control of Coherence between the two signal beams

The mutual coherence of the two signal beams can be controlled by introducing a variable attenuator with transmissivity $\mathcal{T}$ in the idler path [4,7]. The normalized mutual coherence function of the two pump beams is given by

$$\gamma_{12}^{(p)} = \frac{\langle V_1^*(t) V_2(t+\tau_0)\rangle}{\left(\langle I_1\rangle \langle I_2\rangle\right)^{1/2}}, \tag{16}$$

where $V_1(t)$, $V_2(t)$ are the complex amplitudes and $I_1(t)$ and $I_2(t)$ are the corresponding light intensities of the pump beams falling onto the crystals NL1 and NL2. The degree of coherence of the two signal photons is then found to be

$$\left|\gamma_{12}^{(s)}\right| = \left|\gamma_{12}^{(p)}\right| |\mathcal{T}| . \tag{17}$$

The induced coherence between the signal photons is reduced relative to the case where nothing is inserted in the idler path. The inserted attenuator can be considered as a beam-splitter inserted in the path. If the idler photon i_1 from NL1 is reflected off the beamsplitter and detected by a third detector "which path"-information is obtained. If the photon just passes through the beamsplitter no path information is gained. The coherence is therefore reduced since partial "which path"-information is gained. The reduced coherence is made observable through reduced visibility of the interference. Given the degree of coherence between the two signal photons $\left|\gamma_{12}^{(s)}\right|$ the observed visibility can then be written out,

$$\mathcal{V} = \left(\frac{2\left|f_1 f_2\right| \left(\langle I_1\rangle \langle I_2\rangle\right)^{1/2}}{\left|f_1\right|^2 \langle I_1\rangle + \left|f_2\right|^2 \langle I_2\rangle}\right) \left|\gamma_{12}^{(p)}\right| |\mathcal{T}| . \tag{18}$$

This predicted proportionality of the visibility to the transmissivity of the attenuator has in fact been measured [4]. Figure 3 shows the visibility for $|\mathcal{T}| = 0.91$ and $|\mathcal{T}| = 0$. Figure 4 shows the measured visibility of the second order interference pattern as a function of $|\mathcal{T}|$. The insertion of an attenuator in the idler path therefore gives control of the degree of coherence between the signal photons, without changing anything in the signal part of the setup. This control over the degree of coherence can be of interest in applications such as optical communication, quantum computing and integrated optics [7].

Another experiment has been performed by Mandel et al. [6] in which a time dependent modulation (shutter) is introduced in the idler path from NL1 to NL2 in place of the beam-stop (see Fig. 1). It has been shown in this experiment that if an idler photon is rejected at the critical time when it passes the shutter, induced coherence and therefore interference are destroyed. If the filter is opened for a time interval much larger than $1/\Delta\omega$, coherence is induced with maximum visibility of the interference. These results again confirm the explanations that use the "which path"-information of the photons. As soon as some information is obtainable about "which path" the detected photon took, the induced coherence is destroyed, even if a "which path"-measurement with the idler detector has not actually been performed. This reconfirms the statement [4] that "...the state or density operator reflects not only what is known but to an extent also what could be known, in principle, about the photon."

IV. CONCLUSION

When two pairs of photons are created in a parametric down conversion process in two nonlinear crystals, coherence can be induced between the two signal photons without any induced emission by simply aligning the two idler beams. If the idlers are aligned correctly and any "which path"-information is eliminated, coherence is induced between the two originally independent signal photons leading to second order interference. In addition to "which path"-information arguments, QED and Vacuum fluctuation logic give a deeper and better understanding of the induced coherence effect. The degree of coherence can further be controlled by simply inserting a variable attenuator in the idler path. This control of coherence gives rise to various possible applications and studies.

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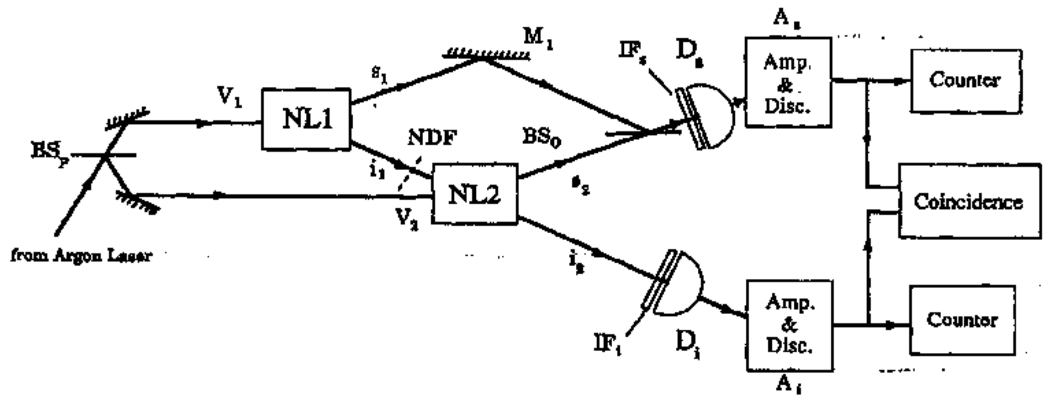

FIG. 1. Outline of the interference experiment. The two nonlinear crystals that are pumped by an argon ion laser each emit a pair of photons (signal s_1, s_2 and idler i_1, i_2). A neutral-density-filter (NDF) or a beamstop can be inserted in the idler path between the two nonlinear crystals NL1 and NL2 in order to control the coherence between s_1 and s_2. [X. Y. Zou, L. J. Wang, and L. Mandel, Phys. Rev. Lett. **67**, 318 (1991)].

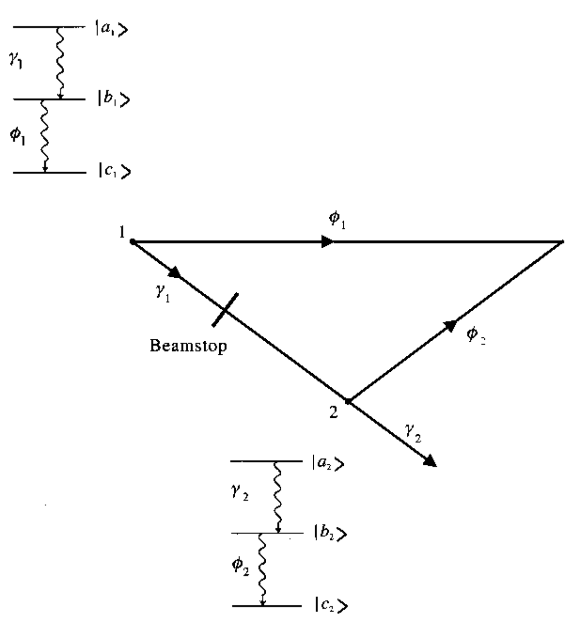

FIG. 2. Three level atom diagrams for analysis of the ZWM-experiment. The photons ϕ_1, ϕ_2 and γ_1, γ_2 that are emitted by the two atoms (1 and 2) can be identified with the signal and idler photons emitted by the two nonlinear crystals NL1 and NL2. [M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge University Press, Cambridge, CB2 2RU, UK, 1997)].

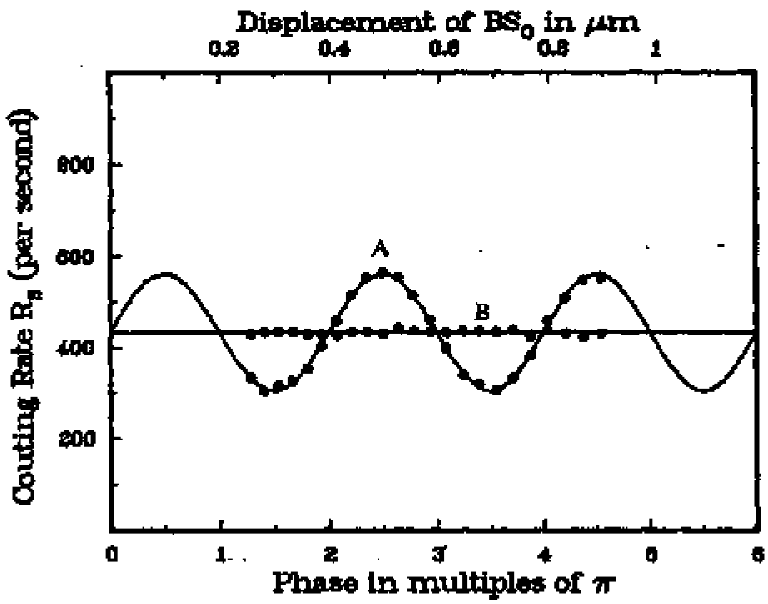

FIG. 3. Measured photon counting rate as a function of path difference variation. Curve A: neutral density filter with $|\mathcal{T}| = 0.91$ inserted between NL1 and NL2. Curve B: beamstop with $|\mathcal{T}| = 0$ [X. Y. Zou, L. J. Wang, and L. Mandel, Phys. Rev. Lett. **67**, 318 (1991)].

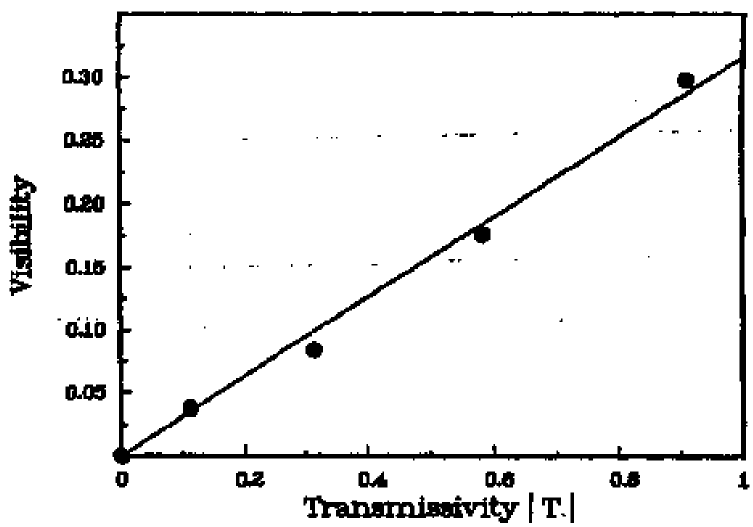

FIG. 4. Measured visibility of the second order interference pattern as a function of amplitude transmissivity $|\mathcal{T}|$ of the filter placed between NL1 and NL2 [X. Y. Zou, L. J. Wang, and L. Mandel, Phys. Rev. Lett. **67**, 318 (1991)].