“Each photon then interferes only with itself. Interference between two different photons never occurs.”

-P.A.M.* Dirac

INTERFERENCE FRINGES PRODUCED BY SUPERPOSITION OF TWO INDEPENDENT MASER LIGHT BEAMS

By G. MAGYAR and Dr. L. MANDEL

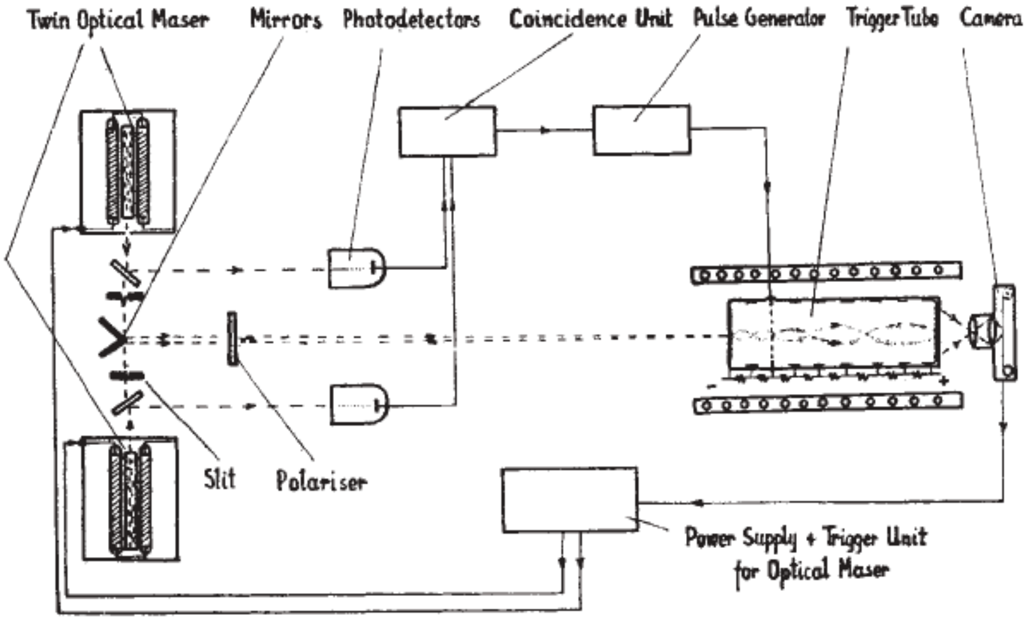


Fig. 1. Outline of the apparatus for recording transient interference fringes

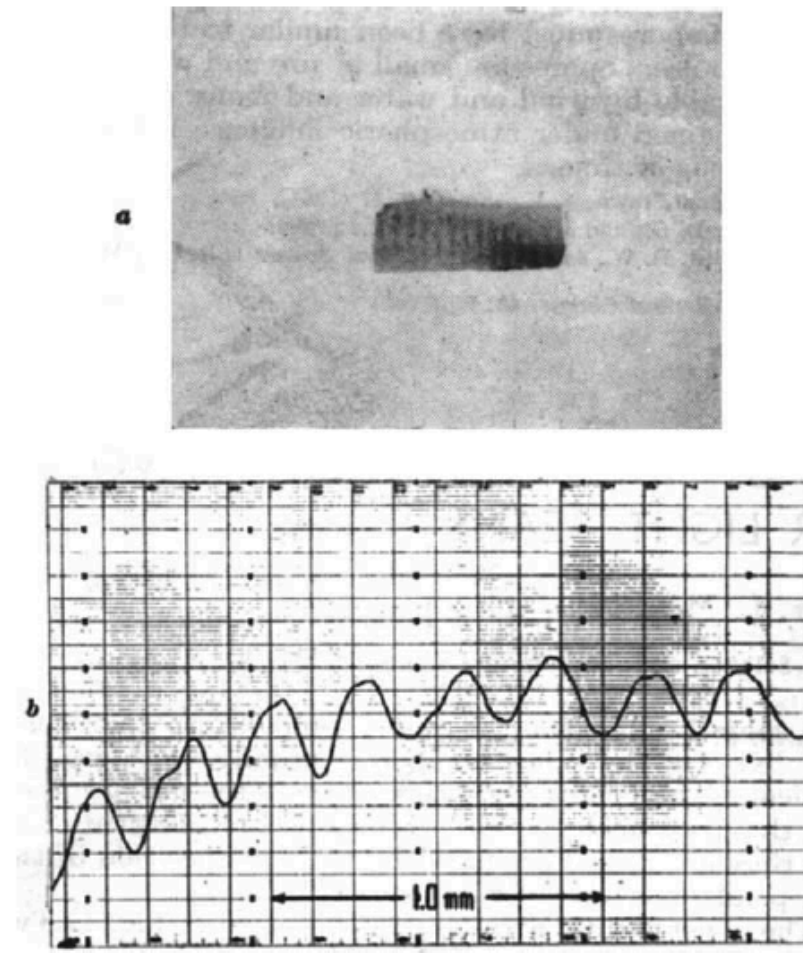
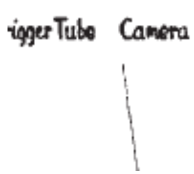


Fig. 2. An example of fringes recorded: (*a*) photograph; (*b*) microphotometer tracing

The flash tubes exciting the two masers are triggered simultaneously; but, as the maser emission from ruby is in the form of a series of random 'spikes' of approximately $\frac{1}{2}$ μsec duration, two light beams are only occasionally emitted in coincidence. The image tube is therefore normally gated-off by a negative bias voltage applied to the grid. Two monitor photodetectors feeding into a coincidence circuit determine when two maser beams emerge in coincidence, and then cause the image tube to be gated-on by a positive pulse of selected duration (30–500 nsec) applied to the grid.



PHYSICAL REVIEW VOLUME 159, NUMBER 5 25 JULY 1967

Interference of Independent Photon Beams*

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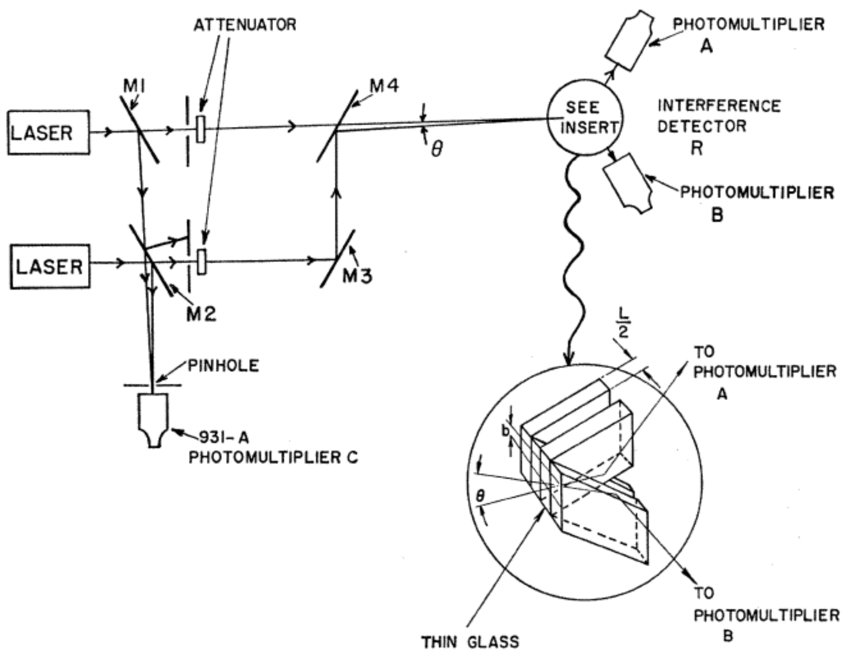
(Received 16 February 1967)

Interference effects produced by the superposition of the light beams from two independent single-mode lasers have been investigated experimentally. It is found that interference takes place even under conditions in which the light intensities are so low that, with high probability, one photon is absorbed before the next one is emitted by one or the other source. Since the average number of registered photons per trial was only about 10, photon correlation techniques were required to demonstrate the interference. The interpretation of the experiment, and the question whether it demonstrates interference between two photons, are discussed.



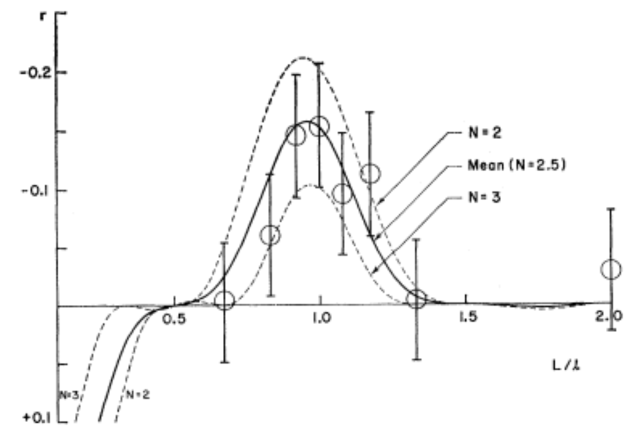


Fig. 3. Experimental results for the correlation coefficient r, together with theoretical curves for $N=2$ and $N=3$ and their mean.

the half fringe spacing coincides with the plate thickness, and the fringe maxima fall on the odd-numbered plates, say, one phototube is expected to register nearly all the photons and the other one almost none. Of course the positions of the fringe maxima are actually unpredictable and random over a succession of trials, but it is clear that, if the number of photons registered by one phototube increases, the number registered by the other one is expected to decrease, provided the fringe spacing is right for the plates. Thus there should be a negative correlation between the numbers of counts n_1 and n_2 registered in the two channels. This is the method we

There is, however, an important proviso that has to be attached if interference fringes are to be observable in the experiment: the light emitted from the two sources must have well-defined phases. With laser sources the condition is easily satisfied, and it was satisfied in the cited experiments [36]. But with atomic sources of definite excitation, for example, no well-defined phase would exist, and interference effects should not be observable. It is easy to see why. If one source consisted of N_1 excited atoms and the other of N_2 excited atoms, we could, in principle, determine from where each photon was emitted by examining the sources. According to quantum mechanics, no interference fringes should then be observable, because one of the two probability amplitudes would be zero.

Observation of Interference Between Two Bose Condensates

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Interference between two freely expanding Bose-Einstein condensates has been observed. Two condensates separated by ~40 micrometers were created by evaporatively cooling sodium atoms in a double-well potential formed by magnetic and optical forces. High-contrast matter-wave interference fringes with a period of ~15 micrometers were observed after switching off the potential and letting the condensates expand for 40 milliseconds and overlap. This demonstrates that Bose condensed atoms are "laser-like"; that is, they are coherent and show long-range correlations. These results have direct implications for the atom laser and the Josephson effect for atoms.

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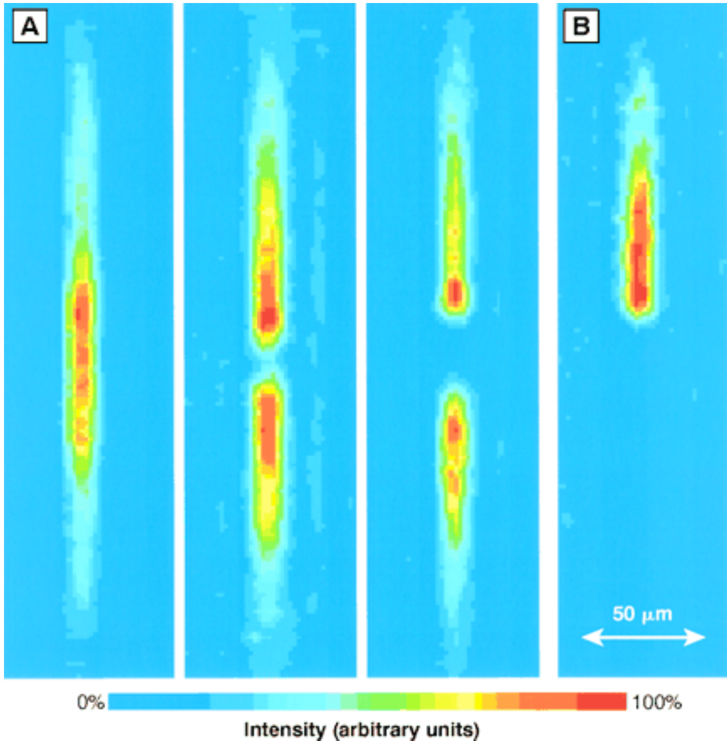


(A) Phase-contrast images of a single Bose condensate (left) and double Bose condensates, taken in the trap. The distance between the two condensates was varied by changing the power of the argon ion laser-light sheet from 7 to 43 mW. (B) Phase-contrast image of an originally double condensate, with the lower condensate eliminated.

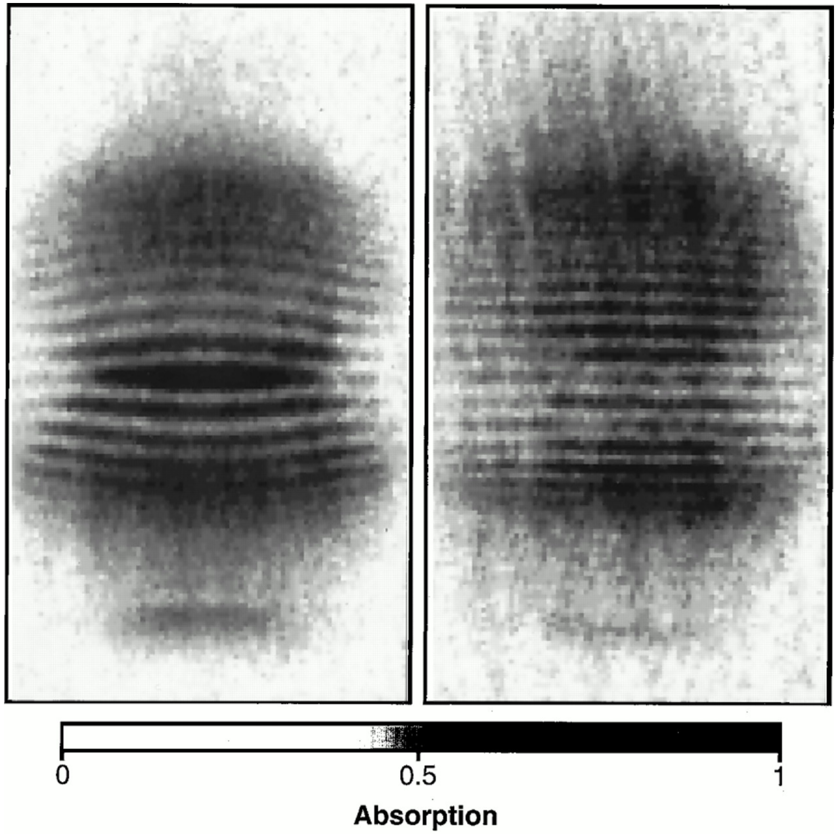
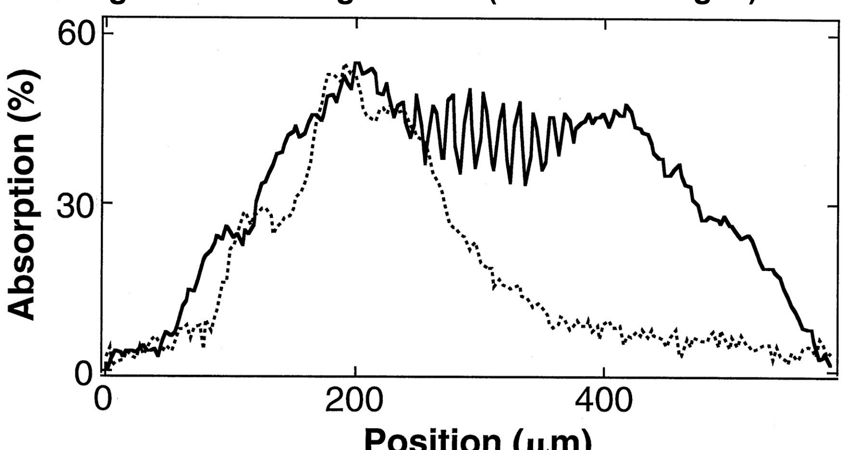


Fig. 2. Interference pattern of two expanding condensates observed after 40 ms time-of-flight, for two different powers of the argon ion laser-light sheet (raw-data images).



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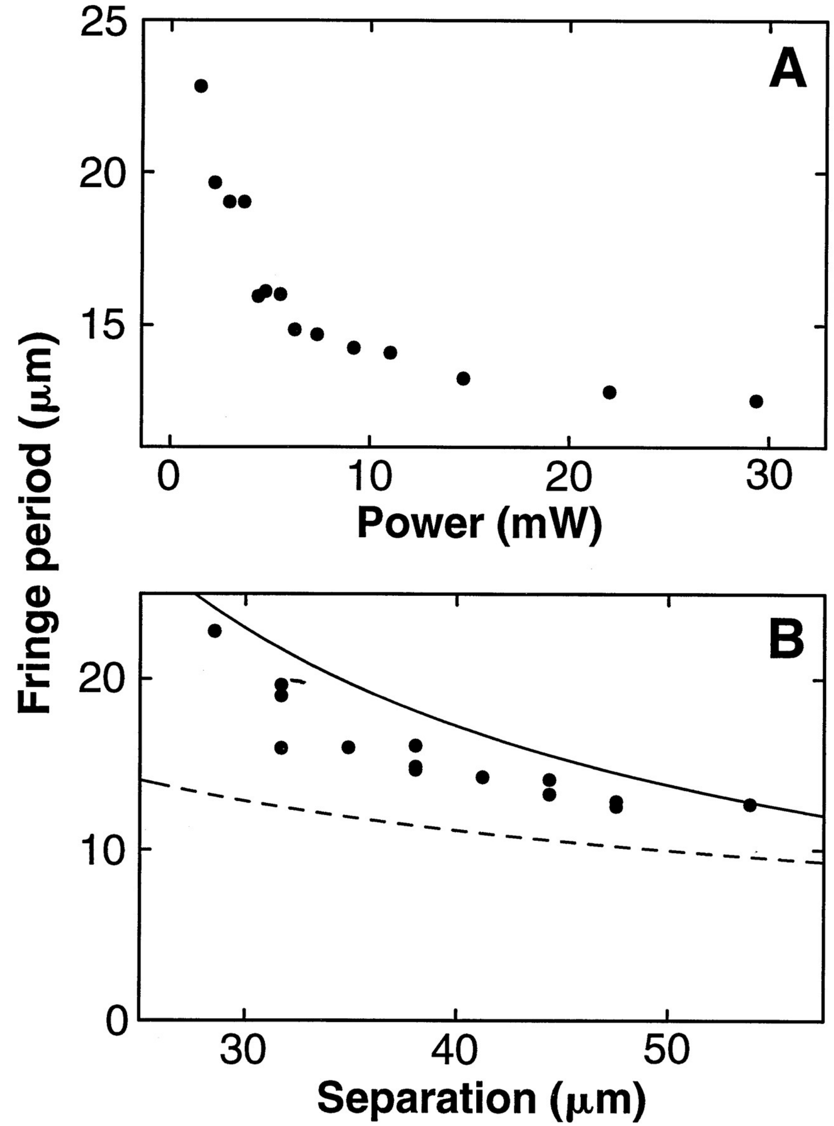

Fig. 3. (A) Fringe period versus power in the argon ion laser-light sheet.

Spontaneous Parametric Down Conversion (Yariv "Quantum Electronics")

$\omega_p = \omega_s + \omega_i$: energy conservation

$\vec{K}_p = \vec{K}_s + \vec{K}_i$: Momentum (inside crystal)

Undergraduate E&M: Classical Wave Description

$$\vec{P} = \chi \vec{E} \Rightarrow P(\omega) = \chi(\omega)\vec{E}(\omega) \Rightarrow P_i(\omega) = \chi_{ij}(\omega)E_j$$

$$P_i^{(\omega)} = \chi_{ij}(\omega)\mathrm{E}_j(\omega) + \chi_{ijk}E_jE_k + \ldots\chi_{ijkl}E_jE_kE_l$$

"4-Wave Mixing"

$$\left(e^{i\omega_1 t} + e^{-i\omega_1 t}\right)\left(e^{i\omega_2 t} + e^{-i\omega_2 t}\right) = \left(e^{i(\omega_1+\omega_2)t} + e^{-i(\omega_1+\omega_2)t}\right) + \left(e^{i(\omega_1-\omega_2)t} + e^{-i(\omega_1-\omega_2)t}\right)$$

$P(\omega_1 + \omega_2) \Rightarrow E\left(\omega_1 + \omega_2\right)$: "Sum-frequency generation"

If $\omega_1 = \omega_2$: "Second harmonic generation"

$P(\omega_1 - \omega_2) \Rightarrow E\left(\omega_1 - \omega_2\right)$: "Difference-frequency generation"

Run it backwards: $UV \rightarrow IR + IR$

No classical explanation. QM: Vacuum modes stimulate process

$$H = \hbar\omega_p\left(n_p + \frac{1}{2}\right) + \hbar\omega_s\left(n_s + \frac{1}{2}\right) + \hbar\omega_i\left(n_i + \frac{1}{2}\right) + H_i$$

$$H_i \sim X^{(2)}\left(a_p - a^\dagger{}_p\right)\left(a_s - a^\dagger{}_s\right)\left(a_i - a^\dagger{}_i\right)$$

Eight terms $\Rightarrow$ many vanish $\rightarrow$ Do not conserve energy

$$a_p a_s{}^\dagger a_i{}^\dagger \Rightarrow \omega_p \Rightarrow \omega_s + \omega_i$$

$$a_p{}^\dagger a_s a_i \Rightarrow \omega_s + \omega_i \Rightarrow \omega_p$$

Treat pump classically: $a_p \rightarrow \varepsilon_p e^{-i\omega_p t}$

$$G_0 = \sqrt{\omega_s\omega_i}\,\frac{2\pi}{n_s n_i}\,\varepsilon_p \chi^{(2)}\left(\omega_{p,}\omega_{s,}\omega_i\right)\frac{sin\left(\frac{\Delta kl}{2}\right)}{\frac{\Delta kl}{2}}$$

$$H^i = \hbar G_0\left[a_s{}^\dagger a_1{}^\dagger e^{-i\omega_p t} + h.\text{c.}\right]$$

Use $\frac{dO}{dt} = \frac{-i}{\hbar}\left[O,H\right] \Rightarrow \left[a_s^\dagger, H\right], \left[a_i^\dagger, H\right]$

$$\Rightarrow a_s^\dagger(t) = \left[a_s^\dagger(0)\cosh G_0 t + i a_i^\dagger(0)\sinh G_0 t\right]e^{i\omega_s t}$$

$$\Rightarrow a_i^\dagger(t) = \left[a_i^\dagger(0)\cosh G_0 t - i a_s^\dagger(0)\sinh G_0 t\right]e^{-i\omega_i t}$$

$$\langle n_s(t)\rangle = \langle n_s(0)\rangle \cosh^2 G_0 t + \left[\langle n_i(0)\rangle + 1\right] sinh^2 G_0 t$$

$$\langle n_i(t)\rangle = \langle n_i(0)\rangle \cosh^2 G_0 t + \left[\langle n_s(0)\rangle + 1\right] sinh^2 G_0 t$$

Response even with no input due to vacuum fluctuations (exactly because $\left[a, a^\dagger\right] = 1$)

For G_0t small, with no input photons, $\left|\Psi^{(t)}\right\rangle = |0\rangle + iG_0 t|1,1\rangle - \frac{(G_0 t)^2}{2}|2,2\rangle + \ldots$

$$P(1,1) = (G_0 t)^2 = \left(\frac{G_o L_n}{c}\right)^2$$

Crystal requirements:

Need non-centro-symmetric crystal (centrosymmetric crystal has $\chi_{ijk} = 0 \Rightarrow$ Need to go for $\chi^{(3)}{}_{ijkl}$)

All systems have $\chi^{(3)}$ but it's even smaller (well, not smaller than 0!)

Usually need birefringent crystal, in order to have phase-matching (momentum conservation) in the presence of crystal dispersion:

$K_p = K_s + K_i \rightarrow \omega_p n(\omega_p)/c = \omega_s n(\omega_s)/c + \omega_i n(\omega_i)/c$ (using $v = c/n = \omega/k$)

E.g., for degenerate SPDC, $\omega_s = \omega_i = \omega_p/2$,

$\omega_p n(\omega_p) = \omega_p n(\omega_s)/2 + \omega_p n(\omega_i)/2 \rightarrow n(\omega_p) = n(\omega_s)/2 + n(\omega_i)/2$.
This is only true if the index doesn't depend on the frequency/wavelength.

To compensate this, we use crystals that have different index of refraction for ordinary and extraordinary polarized light:
E.g., $n_e(\omega_p) = n_o(\omega_s)/2 + n_o(\omega_i)/2$