Experimental Proposal -- Confirmation of a Dielectric Longitudinal Delay of a Bright Interference Fringe

A dielectric-first derivation and two experimental tests in a Mach-Zehnder interferometer

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2026-04-22

One-Sentence Summary. At Mach-Zehnder recombination each arm beam is the in-phase electromagnetic response to the other, so the dielectric slowing mechanism applies directly and the bright fringe propagates at c/2.

Keywords. interference, Mach-Zehnder interferometer, dielectric slowing, dielectric longitudinal delay, constructive interference, energy density, bright interference fringe, refraction, Snell's law, total internal reflection, time-of-flight, speed of light

1. Abstract

A dielectric slows light because the medium responds to the incident electromagnetic wave with an in-phase polarization wave. Maxwell's equations then describe the combined field — incident plus response — propagating at the reduced speed

$$c_{\text{eff}} = \frac{1}{\sqrt{\varepsilon_{\text{eff}}\mu_{\text{eff}}}} = \frac{c}{n}.$$

A dielectric is, at bottom, a coherent recombiner: one in-phase electromagnetic wave riding alongside another.

At Mach-Zehnder recombination, the second arm beam is that in-phase response. Both arms originate from the same coherent source, travel equal paths, and arrive in phase at a bright point. Each beam is, for the other, the in-phase electromagnetic addition that constitutes the dielectric loading. This is not an

analogy to the dielectric case — it is the dielectric mechanism, with the second arm supplying the response sector instead of the medium.

At equal-beam recombination, the arm amplitudes are equal, so each arm is the full-amplitude in-phase response to the other: $k = 1$. The dielectric formula then gives directly

$$c_{\text{eff}} = \frac{c}{2}.$$

The ordinary reading takes the routed output beam and predicts no delay. The experiment is a direct test between these two readings, and it reduces — in the refraction version — to a binary outcome near the critical angle $\theta_c \approx 48.6°$.

2. Introduction

In a linear dielectric, an incident electromagnetic wave induces an in-phase polarization response. Maxwell's equations, applied to the combined field of incident wave plus response, yield the reduced propagation speed c/n. The dielectric index encodes, at bottom, the presence of a second in-phase electromagnetic wave riding alongside the first.

This observation generalizes beyond bulk media. Any configuration that places a second coherent in-phase electromagnetic wave alongside a probe wave should produce the same reduced propagation speed, by the same Maxwell derivation.

A Mach-Zehnder interferometer at its recombination point is precisely such a configuration. Both arm beams originate from the same coherent source, travel equal paths, and arrive in phase at a bright point. Each beam is, from the other's perspective, a full-amplitude in-phase electromagnetic response. The mathematical structure matches the dielectric case exactly, with $k = 1$, so the reduced speed is $c_{\text{eff}} = c/2$.

In Dirac's framing of the superposition principle — *each photon then interferes only with itself* — the two arm beams are two paths of the same coherent state. The loading one arm imposes on the other is therefore self-interference in the strict sense: the photon encountering its own amplitude. The present proposal tests whether that self-interference carries a measurable phase-velocity signature.

The ordinary output-mode analysis disagrees. It normalizes the recombined field through the $1/\sqrt{2}$ routing factor and treats the bright port as a single beam propagating at c. This paper derives the loaded-fringe prediction, frames the disagreement as a direct experimental fork, and proposes two tests: refraction at a glass boundary (geometric) and time-of-flight along a propagation path (temporal). The refraction test reduces the discrimination to a binary outcome near the critical angle $\theta_c \approx 48.6°$, where the loaded reading predicts total internal reflection and the ordinary reading predicts standard transmission.

The logic is one-sided. Constructive interference yields a denser in-phase combined field; destructive interference depletes the field and, in the dark-fringe limit, cancels it rather than producing anything faster. Only the bright-fringe direction of the fork carries a substantive prediction.

3. Theory

3.1. The Dielectric Mechanism

Consider a region in which an electromagnetic probe wave $(\mathbf{E}_1, \mathbf{H}_1)$ is accompanied by an in-phase response wave with amplitude ratio $k \geq 0$,

$$\mathbf{E}_2 = k\,\mathbf{E}_1, \qquad \mathbf{H}_2 = k\,\mathbf{H}_1.$$

The sum fields enter Maxwell's equations through the constitutive relations

$$\mathbf{D} = \varepsilon_0(\mathbf{E}_1 + \mathbf{E}_2) = \varepsilon_0(1+k)\,\mathbf{E}_1 \equiv \varepsilon_{\text{eff}}\,\mathbf{E}_1,$$

$$\mathbf{B} = \mu_0(\mathbf{H}_1 + \mathbf{H}_2) = \mu_0(1+k)\,\mathbf{H}_1 \equiv \mu_{\text{eff}}\,\mathbf{H}_1.$$

In a source-free region,

$$\nabla \times \mathbf{E}_1 = -\frac{\partial \mathbf{B}}{\partial t} = -\mu_{\text{eff}}\frac{\partial \mathbf{H}_1}{\partial t},$$

$$\nabla \times \mathbf{H}_1 = \frac{\partial \mathbf{D}}{\partial t} = \varepsilon_{\text{eff}}\frac{\partial \mathbf{E}_1}{\partial t}.$$

Taking the curl of the first equation and using $\nabla \cdot \mathbf{E}_1 = 0$ gives the wave equation

$$\nabla^2\mathbf{E}_1 - \varepsilon_{\text{eff}}\mu_{\text{eff}}\frac{\partial^2 \mathbf{E}_1}{\partial t^2} = 0,$$

so the combined field propagates at

$$c_{\text{eff}} = \frac{1}{\sqrt{\varepsilon_{\text{eff}}\mu_{\text{eff}}}} = \frac{1}{\sqrt{\varepsilon_0\mu_0(1+k)^2}} = \frac{c}{1+k}.$$

This result depends only on the existence of an in-phase electromagnetic response with amplitude ratio k. It does not depend on the physical origin of that response.

3.2. Two Physical Realizations

Linear dielectric. In a transparent linear dielectric, $\mathbf{E}_2$ is the electromagnetic field of the medium's polarization response, and the amplitude ratio is the electric susceptibility, $k = \chi_e$ (analogously χ_m for the magnetic response). The standard reduced-speed formula c/n follows with $n = \sqrt{(1+\chi_e)(1+\chi_m)}$.

Mach-Zehnder recombination. At the recombination point of a Mach-Zehnder interferometer, $\mathbf{E}_2$ is the second arm beam. Both arms originate from the same coherent source, travel equal paths, and arrive in phase at a bright point. Each beam is, from the other's perspective, a full-amplitude in-phase electromagnetic response. At full constructive interference $\mathbf{E}_2 = \mathbf{E}_1$, so $k = 1$ without further substitution, and

$$c_{\text{eff}} = \frac{c}{2}.$$

The physical realizations differ — medium polarization versus free-propagating beam — but the mathematical structure, and therefore the predicted propagation speed, is identical. The dielectric result is not transferred by analogy; it applies directly, because the mechanism is the same.

3.3. Why the Split Phase Is Different

The split and recombination use the same physical element (a 50/50 beam splitter) but are not the same operation.

The split takes one beam and produces two equal beams from it. Its purpose is to prepare coherent arm beams; no loaded interference fringe is formed.

Recombination takes two coherent equal beams and concentrates them into a single signal distributed across two output channels. The bright channel receives the constructive-interference fringe; the dark channel receives nothing. Together they account for the full input energy — the fringe profile $\cos^2 + \sin^2 = 1$ sums to unity.

The dielectric loading question belongs to recombination, where two in-phase equal beams combine, not to the split.

4. Proposed Experiments

4.1. The Two Readings

Each arm carries amplitude E_0 (energy density u). At recombination the two coherent equal beams combine: the bright fringe has amplitude $2E_0$ and energy density $4u$; the dark fringe has 0. The fringe profile $\cos^2 + \sin^2 = 1$ distributes the full input energy across the two output channels.

The dielectric loading applies to the combined field at the bright fringe. With $k = 1$ the dielectric result gives $c_{\text{eff}} = c/2$ (see Discussion: Energy and Flux Accounting for the full energy and routing accounting).

The two readings differ in the phase velocity assigned to the bright fringe:

- ordinary output reading: $v_{\text{bright}} = c$
- loaded-fringe reading: $v_{\text{bright}} = c/2$

Two experiments can probe this phase velocity: refraction at a glass boundary (geometric) and time-of-flight along a propagation path (temporal). Both access the same underlying wavevector magnitude $|k| = n_{\text{eff}}\,\omega/c$ in the overlap region; they are not independent confirmations but complementary observation channels.

4.2. Refraction Test

The simplest test to discriminate the two readings is geometric. Snell's law at a boundary between two media,

$$n_1 \sin\theta_i = n_2 \sin\theta_r,$$

is tangential-wavevector conservation: $|k|_{\text{tangential}}$ is preserved at the boundary, and $|k| = n\,\omega/c$. The refraction angle therefore reads off the wavevector magnitude of the incident wave. The testable content of the $c_{\text{eff}} = c/2$ claim is that the combined field at the bright fringe carries $|k| = 2\omega/c$ in the overlap region, which at a boundary with glass of index n_g bends the beam to

$$\sin\theta_r = \frac{2}{n_g}\sin\theta_i,$$

twice the ordinary prediction.

Setup. Arrange the Mach-Zehnder so the two arm beams are collinear at the recombiner output. Isolate one bright fringe with an aperture and let it propagate toward a glass slab ($n_g \approx 1.5$) at oblique incidence θ_i. A reference beam taken directly from the laser is sent to the same slab at the same θ_i for standard-refraction comparison.

The two arm beams remain spatially coincident within the apertured beam, so each is still the in-phase response to the other and the dielectric loading argument persists as long as they propagate together.

Predictions.

- *Ordinary reading* ($n_{\text{eff}} = 1$): standard refraction, identical to the reference, $\sin\theta_r = \sin\theta_i/n_g$.
- *Loaded-fringe reading* ($n_{\text{eff}} = 2$): $\sin\theta_r = (2/n_g)\sin\theta_i = (4/3)\sin\theta_i$.

For the loaded reading a critical angle appears at

$$\sin\theta_c = \frac{n_g}{n_{\text{eff}}} = 0.75, \qquad \theta_c \approx 48.6^\circ.$$

Above that incidence angle the loaded reading predicts total internal reflection — no transmitted beam — while the ordinary reading still predicts standard transmission.

At $\theta_i \gtrsim 49^\circ$ the experiment reduces to a binary discriminator: either the bright fringe transmits into the glass or it does not. No timing measurement is required.

4.3. Time-of-Flight Test

If the refraction test is positive, a direct temporal confirmation is to propagate the fringe and measure its group delay.

Use a coherent source, modulate it, split it into two arms, and recombine the arms so they form stable fringes. Then:

1. isolate one bright interference fringe with an aperture
2. propagate that selected fringe over distance L
3. propagate a matched reference beam over the same distance
4. compare delay slopes $d\tau/dL$

The ordinary reading predicts equal slopes. The loaded-fringe reading predicts a larger slope for the bright fringe.

For the equal-beam limit,

$$\tau_{\text{bright}} - \tau_{\text{ref}} \approx \frac{L}{c}.$$

So at 1 m the extra delay is about 3.34 ns, and at 10 m it is about 33.4 ns.

5. Discussion: Energy and Flux Accounting

The dielectric argument above establishes $c_{\text{eff}} = c/2$ from the loading structure alone. The following energy and flux calculations are consistency checks, not the primary argument.

Throughout this document u denotes energy density (J/m^3), not intensity (W/m^2); the two are related by $I = u\,v$ where v is the propagation speed, and they differ between the two readings.

Energy density at the bright center. With $k = 1$ and arm amplitude E_0 (energy density u),

$$\mathbf{E}_{\text{tot}} = 2E_0, \qquad \mathbf{H}_{\text{tot}} = 2H_0,$$

and the instantaneous energy density is

$$u_{\text{tot}} = 4u.$$

This is twice the input laser energy density $2u$ and four times each arm's energy density u. Across the fringe profile,

$$u(x) = 4u \cos^2\left(\frac{\Delta\phi(x)}{2}\right),$$

averaging to $2u$ over a full fringe period. The dark fringe carries 0, so the spatial redistribution accounts for the full input energy.

Instantaneous derivation. No time averaging is needed. At a full constructive-interference point, $\mathbf{E}_1(t) = \mathbf{E}_2(t) = E_0(t)$ and $\mathbf{B}_1(t) = \mathbf{B}_2(t) = B_0(t)$, so $\mathbf{E}_{\text{tot}}(t) = 2E_0(t)$, $\mathbf{B}_{\text{tot}}(t) = 2B_0(t)$, and

$$u_{\text{tot}}(t) = \frac{\varepsilon_0}{2}|\mathbf{E}_{\text{tot}}(t)|^2 + \frac{1}{2\mu_0}|\mathbf{B}_{\text{tot}}(t)|^2 = 4u.$$

The factor of four is instantaneous and exact: amplitude doubles, energy density quadruples.

Output routing. The recombiner maps the overlap into two output spatial modes. For a lossless 50/50 recombiner,

$$\mathbf{E}_+ = \frac{\mathbf{E}_1 + \mathbf{E}_2}{\sqrt{2}} = \sqrt{2}\,E_0, \qquad \mathbf{E}_- = \frac{\mathbf{E}_1 - \mathbf{E}_2}{\sqrt{2}} = 0,$$

and likewise for the magnetic fields. The $1/\sqrt{2}$ routing factor, combined with the $1/\sqrt{2}$ that already reduced the arm amplitudes at the initial split, returns the full input energy to the bright port:

$$u_+ = 2u, \qquad u_- = 0.$$

The ordinary reading starts from this $2u$ output and finds no anomalous refraction or delay. The loaded-fringe reading starts from the $4u$ raw overlap and predicts $c/2$. These energy-accounting relations are consistent with both readings; they do not by themselves decide which propagation speed is physical. That discrimination is what the refraction and time-of-flight experiments provide.

6. Conclusion

The experiments test which object should be treated as the propagating fringe after recombination:

- the ordinary normalized output mode, with $n_{\text{eff}} = 1$
- or the isolated raw constructive-interference fringe, with $n_{\text{eff}} = 2$

For the refraction test, if the bright fringe transmits into the glass at $\theta_i \gtrsim 49°$ together with the reference, the ordinary reading wins. If the bright fringe undergoes total internal reflection while the reference still transmits, the loaded-fringe reading is supported.

For the time-of-flight test, if the measured delay matches the reference, the ordinary reading wins. If the delay approaches the $c/2$ prediction in the equal-beam limit, the loaded-fringe reading is supported.

7. Acknowledgments

We thank Celso L. Ladera of Universidad Simón Bolívar, Caracas, for introducing one of us (A.M.R.) to Dirac's dictum on self-interference during his undergraduate optics course.

8. References

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