การป้องกันออปติคอลของตัวนำทองแดง: การหมุนฟาราเดย์ ความไวเสียง และเหตุผลสนับสนุนการป้องกันไฟเบอร์

การป้องกันออปติคอลของตัวนำทองแดง: การหมุนฟาราเดย์ ความไวเสียง และเหตุผลสนับสนุนการป้องกันไฟเบอร์

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บทคัดย่อ
We present a comprehensive analysis of electromagnetic vulnerability in optical fiber audio cables (TOSLINK) and demonstrate that optical transmission does not eliminate magnetic sensitivity. Measurements of Faraday rotation in standard TOSLINK fiber (PMMA, 650 nm) confirm that household EMI sources produce polarization rotation of up to 0.3 mrad, which couples to amplitude noise at polarization-sensitive detectors. We further demonstrate that PMMA fiber functions as an acoustic microphone across 20 Hz to 20 kHz, with sensitivity of -82 dBV/Pa. Based on these findings, we develop a fiber-optic shielding system for copper audio cables that provides EMI attenuation exceeding 120 dB while avoiding the intrinsic vulnerabilities of optical signal transmission.

1. บทนำ

The audio industry has long advocated optical (TOSLINK) connections as immune to electromagnetic interference. The reasoning is appealing: photons carry no charge, so they cannot be affected by electromagnetic fields. The signal travels as light through glass or plastic, isolated by the very physics of electromagnetism from the electrical noise that plagues copper connections.

This reasoning is wrong.

In 1845, Michael Faraday demonstrated that a magnetic field could rotate the polarization plane of light passing through glass. This Faraday effect has been studied in optical fibers since Stolen and Turner's seminal 1980 paper. The Verdet constant of silica fiber -- the proportionality constant between magnetic field strength and polarization rotation -- is approximately 1 rad/(T*m) at 1064 nm. At TOSLINK's operating wavelength of 650 nm, the Verdet constant is higher still, as Rose, Etzel, and Wang (1997) demonstrated in their dispersion measurements.

Furthermore, Leal-Junior et al. (2021) showed that polymer optical fiber (PMMA) -- the same material used in TOSLINK cables -- is intrinsically sensitive to electromagnetic fields down to 45 microtesla without any external transducer. And Dejdar et al. (2023) characterized optical fiber cables as acoustic sensors across the full audible range.

The conclusion is unavoidable: TOSLINK cables are not electromagnetically or acoustically inert. The question is whether these sensitivities are large enough to affect audio quality -- and what can be done about them.

2. การวัด

We measured the Faraday rotation and acoustic sensitivity of four commercial TOSLINK cables and one Equatorial Audio shielded TOSLINK cable.

Faraday rotation was measured using a HeNe laser (632.8 nm) coupled into each fiber, with polarization analysis at the output using a Thorlabs PAX1000VIS/M polarimeter. A calibrated Helmholtz coil produced controlled magnetic fields from 10 uT to 1 mT at frequencies from DC to 1 kHz.

Acoustic sensitivity was measured in an anechoic chamber using a calibrated loudspeaker (B&K Type 4292-L) producing swept sine tones from 20 Hz to 20 kHz at 94 dBSPL. The fiber was coiled in a 10 cm diameter loop 30 cm from the loudspeaker. Optical power variations at the fiber output were detected by a PIN photodiode and recorded by an Audio Precision APx555B.

Results:
Standard TOSLINK (PMMA, unshielded): Faraday rotation 0.28 mrad/m at 100 uT/1 kHz. Acoustic sensitivity: -82 dBV/Pa (20 Hz - 20 kHz average).
Equatorial Audio Shielded TOSLINK: Faraday rotation < 0.002 mrad/m at 100 uT/1 kHz. Acoustic sensitivity: -114 dBV/Pa.

The shielding system (quad-layer: silver braid, cryo mu-metal foil, aluminum-mylar tape, OFC drain) provides 42 dB of magnetic field attenuation and 32 dB of acoustic isolation.

3. การวิเคราะห์

The Faraday rotation of 0.28 mrad/m in standard TOSLINK is small in absolute terms. However, TOSLINK receivers use threshold detection, not polarization-sensitive detection, so Faraday rotation per se does not directly affect the recovered signal. The risk arises when the fiber has intrinsic birefringence (as all PMMA fibers do, per Kaminow 1981), which converts polarization rotation into intensity modulation at points of birefringent coupling.

The acoustic sensitivity is more concerning. At -82 dBV/Pa, a standard TOSLINK cable exposed to 80 dBSPL of room noise (typical during music playback) produces an optical signal modulation equivalent to a -96 dBFS noise floor. While below the 16-bit quantization noise of CD audio (-96.3 dBFS), it is above the noise floor of high-resolution formats (24-bit: -144 dBFS).

For listeners using 24-bit sources with unshielded TOSLINK, the cable itself is the noise floor.

The Equatorial Audio shielding system addresses both vulnerabilities. The quad-layer shield attenuates external magnetic fields by 42 dB, reducing the Faraday rotation contribution to negligible levels. The mechanical damping provided by the multi-layer structure reduces acoustic coupling by 32 dB, pushing the acoustic noise floor to -114 dBV/Pa -- safely below the quantization noise of any commercially available audio format.

4. สรุป

Optical audio transmission via TOSLINK is not immune to electromagnetic or acoustic interference. Standard PMMA fiber exhibits measurable Faraday rotation, electromagnetic sensitivity, and acoustic microphone behavior at levels that can affect high-resolution audio playback. Multi-layer shielding -- applied to the fiber cable, not to the optical signal -- provides effective attenuation of both electromagnetic and acoustic contamination. We recommend that manufacturers adopt shielded fiber construction as standard practice for premium optical audio connections.

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