Oscillating Test of the Isotropic Shift of the Speed of Light

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In this Letter, we present an improved constraint on possible isotropic variations of the speed of light. Within the framework of the standard model extension, we provide a limit on the isotropic, scalar parameter $\tilde{\kappa}_{\mathrm{tr}}$ of $3 \pm 11 \times 10^{-10}$, an improvement by a factor of 6 over previous constraints. This was primarily achieved by modulating the orientation of the experimental apparatus with respect to the velocity of Earth. This orientation modulation shifts the signal for Lorentz invariance to higher frequencies, and we have taken advantage of the higher stability of the resonator at shorter time scales, together with better rejection of systematic effects, to provide a new constraint.

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Introduction.—Experimental tests of Lorentz invariance (LI) have played a prominent role in the progress of physics over the last 120 years. Beginning with failed searches for the luminiferous aether wind and moving to the confirmation of special relativity, the results of speed of light experiments provide essential confirmation for theories at the foundation of modern physics. A renaissance of interest in tests of LI has been driven by the postulates of new theories that violate LI while attempting to unify general relativity and the standard model [1–4].

Resonator experiments search for violations of LI through position, velocity, and orientation dependencies of the speed of light. A theoretical framework is required to report and interpret the results of these experiments. An early example was the Robertson-Mansouri-Sexl framework [5,6], where limits are set on parameters which represent deviations from the expected results of special relativity. In this framework, the experiment is analyzed with respect to the reference frame of the cosmic microwave background. Recently a more comprehensive framework—the standard-model extension (SME) [7,8]—has been widely used. The SME is a parametrization of all possible violations of LI by known fields and is analyzed with respect to a sun-centered celestial equatorial frame (SCCEF) moving inertially with respect to the cosmic microwave background. The SME has only recently been extended from the minimal SME to include operators of higher dimension [9,10]. In these theories, the choice of reference frame is arbitrary; however, any nonzero parameter represents a violation of LI. In the photon sector of the minimal SME, there are 19 independent parameters representing violations of LI through various deviations in the universal speed of light.

The parameters of the photon sector of the SME are accessed through astrophysical observations and terrestrial resonator experiments with vastly differing sensitivities based on the properties of the relevant parameter and the experiment. The constraints on the 10 parameters representing vacuum birefringence ($\tilde{\kappa}^{jk}_{e+}$ and $\tilde{\kappa}^{jk}_{o-}$) are based on astrophysical observations of pulsed sources and broadband polarized sources [11]. The vast distances involved with astrophysical observation have allowed tight constraints to be placed on the birefringent parameters at the level of 10^{-32}, and these parameters are generally set to zero in calculations for the remaining 9 parameters.

The remaining SME parameters together create a time-independent but orientation-dependent modification to the speed of light parametrized in the SCCEF. Essentially, the isotropic $\tilde{\kappa}_{\mathrm{tr}}$ is an average shift over all possible directions: $\tilde{\kappa}^{jk}_{e-}$ represents a directional dependence in the speed of light and $\tilde{\kappa}^{jk}_{o+}$ is the relative difference between light moving parallel and antiparallel to some particular direction. Laboratory-based experiments are sensitive to combinations of these SME parameters through Lorentz transforms from the SCCEF to the laboratory reference frame, and a time dependence on the parameters is induced through the relative orientation of the Earth.

Advanced, modern versions of Michelson-Morley (MM) experiments have constrained the even-parity parameter $\tilde{\kappa}^{jk}_{e-}$ terms to the 10^{-17} level and the odd-parity $\tilde{\kappa}^{jk}_{o+}$ terms to 10^{-13} level [12,13]. The even-parity symmetry of the MM experiments gives rise to first-order sensitivity to the even-parity terms and a reduced sensitivity to the odd-parity terms. The reduction in sensitivity to the odd-parity $\tilde{\kappa}^{jk}_{o+}$ terms depends on the velocity of the experiment, and the disparity in sensitivity is given by the velocity of the Earth normalized to the speed of light: $\beta = \frac{v_{\oplus}}{c} \simeq 10^{-4}$ [11].

The isotropic SME parameter $\tilde{\kappa}_{\mathrm{tr}}$ suffers a further β^2 ($\sim 10^{-8}$) reduction in sensitivity from even-parity MM experiments [14]. However an odd-parity resonator has only a first-order, β, reduction in sensitivity to $\tilde{\kappa}_{\mathrm{tr}}$ [15] and provides an avenue to improve the constraints on the frame-dependent isotropic shift of the speed of light.

Tests of the isotropic shift of the speed of light.—The SME parameter $\tilde{\kappa}_{\mathrm{tr}}$ can be derived from numerous types of experiments. The absence of photon decay events from high-energy cosmic rays yields a constraint at the level of 10^{-20} [16], based on assumptions of the high-energy dynamics. Further constraints are derived from particle accelerators, the lack of vacuum Cherenkov radiation from relativistic electrons [17,18] at the 10^{-11} level, and the characterization of synchrotron emission rates at the 10^{-15} level [18]. Contributions of $\tilde{\kappa}_{\rm tr}$ to the anomalous magnetic moment of the electron can be calculated and compared to the standard value, giving a constraint at the 10^{-8} level.

However, the experiments mentioned above contain model-dependent assumptions or measure $\tilde{\kappa}_{\rm tr}$ indirectly [19]. Direct measurements of $\tilde{\kappa}_{\rm tr}$ can be derived from experiments using spectroscopy on fast-moving ions to measure the Robertson-Mansouri-Sexl time-dilation parameter α [20,21]. The SME parameter $\tilde{\kappa}_{\rm tr}$ can be obtained from these experiments by considering the phase velocity of signals traveling in opposite directions in the laboratory frame moving with respect to a sun-centered reference frame which provides a constraint at the 10^{-8} level [15].

Resonator tests of LI yield the tightest constraints for direct measurements of $\tilde{\kappa}_{\rm tr}$. Rotating, even-parity microwave resonators have determined $\tilde{\kappa}_{\rm tr}$ as $-15 \pm 7.4 \times 10^{-9}$ [14] and a rotating odd-parity microwave resonator reached the 10^{-7} level, limited by vibrational noise [22]. The best constraint yet reported is by an odd-parity optical resonator with $\tilde{\kappa}_{\rm tr} = 3.4 \pm 6.7 \times 10^{-9}$, from an experiment stationary in the laboratory [23] using counterpropagating modes. The experiment reported here is an improved version of [23], utilizing orientation modulation together with alignment control to reduce systematic errors and improve the constraint on the isotropic shift of the speed of light by a factor of 6.

Asymmetric optical resonator and optical setup.—A violation of LI in resonator experiments manifests itself as a shift in the resonant frequency of an optical cavity dependent on the orientation with respect to the SCCEF. In this experiment, we use the frequency difference of counterpropagating modes as the observable, and the orientation of the cavity in the laboratory frame is rotated 180° approximately every 10 minutes. The resonant cavity is an odd-parity asymmetric ring resonator with a dielectric in one arm of the ring to provide the necessary asymmetry. The dielectric is a Brewster's angled UV-fused silica prism ($n = 1.44$) with an optical path length through the prism of 14 mm. The cavity has a finesse of 860 and a free spectral range of 3.87 GHz and is housed in a single machined aluminum block with high-reflectivity dielectric mirrors. The cavity is designed so that the optical path strikes the Brewster's angled prism at the correct angle to minimize losses for p-polarized light and the lack of orthogonal surfaces inhibits the generation of reflected modes; see Fig. 1. There are ring piezoelectric transducers on one of the mirrors to enable adjustments of the cavity length to ensure continuous long-term operation of the experiment.

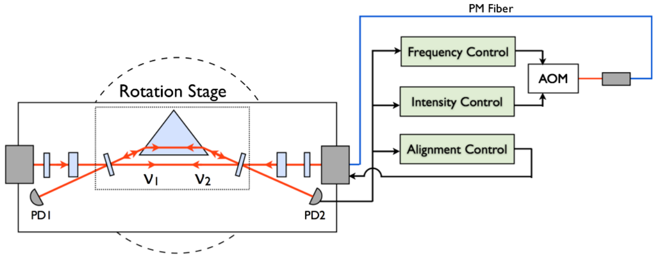

FIG. 1 (color online). Diagram of the experiment showing the asymmetric ring resonator; there is an equivalent setup for the counterpropagating mode. PD—photodiode; PM fiber—polarization-maintaining optical fiber.

A 1064 nm diode-pumped, nonplanar ring laser is split into two paths that are independently frequency locked to counterpropagating modes using the standard Pound-Drever-Hall (PDH) technique [24] with a 987 kHz modulation frequency. The observable in the experiment is the frequency difference of counterpropagating resonant modes. The two incoming beams are mode matched to the fundamental mode of the resonator ensuring complete overlap of the spatial mode of the resonator and we verify that we are exciting the fundamental transverse mode.

The use of counterpropagating modes allows the rejection of systematic cavity length fluctuations driven by environmental fluctuations. A change in the optical path length is common to both directions of propagation and will be rejected in the frequency difference signal. This is a major advantage of the asymmetric ring resonator and the experiment reported here could be performed without temperature control or vibration isolation with no loss of performance.

To measure the frequency difference between the counterpropagating modes, the laser is frequency locked to the resonator by two independently actuated acousto-optic modulators (AOMs) in the double pass configuration [25], and the difference frequency is monitored by a frequency counter. This is achieved by frequency shifting one of the incoming beams by an AOM by a fixed 160 MHz and then controlling the frequency of the laser to lock to the propagating mode of the resonator. The second beam passes through an independent AOM to lock to the counterpropagating mode, and any frequency corrections are provided by the second AOM [23]. Thus, the correction signal sent to the second AOM represents the frequency difference between the two counterpropagating modes, and in this signal we search for violations of LI.

Spatial modulation and alignment control.—By rotating the asymmetric resonant cavity by 180° in the laboratory, the sign of expected signal for violations of LI, caused by nonzero $\tilde{\kappa}_{\rm tr}$, is reversed. This is due to the change in orientation of the cavity with respect to the velocity of the Earth, in a similar manner that the rotation of the Earth gives rise to expected signals with sidereal period. The orientation modulation of the cavity is analogous to the optical chopping technique widely used in experiments to push measurements into spectral regions with less noise. The orientation modulation was performed by mounting the asymmetric cavity, beam preparation optics, and reflection photodiodes for the PDH lock on an optical breadboard attached to a computer-controlled rotation stage (Newmark Systems RT-5-10). By mounting the frequency control photodiodes (New Focus PDA10CS) on the rotation stage with the cavity, many of the systematic effects associated with rotation are reduced. The laser is transported to the breadboard through two polarization-maintaining optical fibers secured and aligned along the axis of rotation.

The output collimators of the optical fibers are housed in three-axis piezoelectrical mounts to allow active alignment control. The X and Y axes of the mounts are dithered at a fixed frequency with a 90° phase shift between the two directions. The light reflected from the resonator is demodulated through lock-in amplifiers and the in-phase and quadrature signals give the error signal for the two directions of alignment, similar to the technique presented in [26]. Two different dither frequencies are employed to prevent cross talk between the two counterpropagating modes (417 and 479 Hz) and are chosen beyond the mechanical resonance of the mount and away from the vibrational peak associated with rotation. Further control systems are employed to maintain constant optical power by varying the rf power sent to the AOM.

Experimental operation and systematic effects.—Inspection of the frequency stability of the laser locked to one of modes showed maximum frequency stability on time scales of ~10 minutes. We thus chose a data collection period of 617 seconds at each orientation followed by approximately 100 seconds of dead time as the experiment rotates the 180° to the other orientation. The rotation stage provides a voltage signal during movement and this was recorded concurrently with the frequency difference data to enable accurate demodulation. The back-and-forth motion of the rotation stage puts minor strain on the optical fibers used to deliver the laser to the breadboard, but the effect is minimized through alignment control, and the experiment easily remained locked for weeks without intervention.

The asymmetric ring resonator is oriented with the plane of propagating in the horizontal plane, and the propagation in the dielectric is oriented in the east-west direction during the data acquisition phase. The asymmetric ring resonator is sensitive to the Sagnac effect from the rotation speed of the experiment in the laboratory, but the Sagnac effect only occurs during rotation, and we only acquire data while the experiment is stationary. The Sagnac effect during rotation is at the 1×10^{-13} fractional frequency level and is below the short-term noise of the experiment, so no effect is observed.

The reversal of the orientation of the asymmetric ring resonator reverses the effect on the resonant frequency from nonreciprocal effects, which arise from the presence of magnetic fields in the laboratory. The combination of Faraday rotation and birefringence in the dielectric prism results in a 2×10^{-13} fractional frequency difference in the two counterpropagating modes. The change in orientation of the experiment reverses the direction of light propagation with respect to the magnetic field and the frequency difference is reversed, but this is a constant offset between the two orientations. To affect the measurement of $\tilde{\kappa}_{\mathrm{tr}}$, the magnetic field strength must vary and measurements in the laboratory show the magnetic field is constant to 10^{-3}, which corresponds to a measurement of $\tilde{\kappa}_{\mathrm{tr}}$ at the 10^{-11} level.

Data analysis and limitations.—The experiment ran for 66 days from the 19th of May 2011 and reversed orientation 6129 times during 50 days of data acquisition. Any violation of LI would be apparent in the data as a sidereal modulation with a sign change corresponding to every 180° rotation of the experiment. To demodulate the signal for LI from the acquired raw data, the following procedure was performed: Stationary periods of measurement were identified through analysis of the rotation stage signal, and data taken with the apparatus in motion were discarded. An average of the counterpropagating mode difference frequency was taken over the 617 seconds that the apparatus was stationary to produce a single point. The difference between successive data points was calculated (with appropriate sign changes), and this effectively demodulates the rotation of the cavity. These demodulated data now contain the putative LI signal at the sidereal period, but systematic effects occurring at the sidereal period have been shifted to higher frequency. Least squares regression is used to fit the sine and cosine terms to the processed data and from amplitude and error of the fits, a determination of the SME parameters is made; see Table I. The demodulated data and determinations of $\tilde{\kappa}_{\mathrm{tr}}$ are shown in Fig. 2.

The stationary positions of the cavity are orientated in an east-west direction to maximize the sensitivity to LI violations, and the analysis of the data is similar to that in [23]. The standard SME sun-centered equatorial reference frame

TABLE I. Sensitivity coefficients of $\tilde{\kappa}_{\mathrm{tr}}$ for this experiment using the short data set approximation.

Modulation	Coefficient	Numerical Value
$\sin(\omega_\oplus \mathrm{T}_\oplus)$	$-2\beta\cos(\eta)\cos(\Omega_0) \times [(\mathcal{M}_{\mathrm{DB}})^{XZ}_{\mathrm{lab}} - (\mathcal{M}_{\mathrm{DB}})^{ZX}_{\mathrm{lab}}]$	$2.8 \times 10^{-5}\cos(\Omega_0)$
$\cos(\omega_\oplus \mathrm{T}_\oplus)$	$2\beta\sin(\Omega_0) \times [(\mathcal{M}_{\mathrm{DB}})^{XZ}_{\mathrm{lab}} - (\mathcal{M}_{\mathrm{DB}})^{ZX}_{\mathrm{lab}}]$	$2.57 \times 10^{-5}\sin(\Omega_0)$

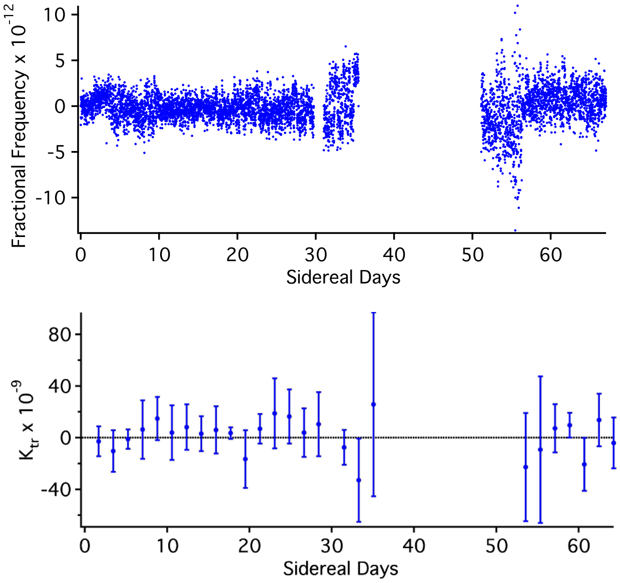

FIG. 2 (color online). Difference in resonant frequency of counterpropagating modes. Processed time series data (top) and the values obtained for $\tilde{\kappa}_{\rm tr}$ from the data set split up into ~two-day portions (bottom).

and the short data set approximation were employed [27] due to the limited data collection time. The value of the isotropic shift of the speed of light $\tilde{\kappa}_{\rm tr}$ was determined to be $3 \pm 11 \times 10^{-10}$, a factor of 6 better than the previous constraint [23]. The odd-parity parameter $\tilde{\kappa}_{o+}^{XZ}$ was $1.6 \pm 2.2 \times 10^{-13}$, a factor of 2 from the current constraints [12,13]. The limit to these measurements is set by the white frequency noise of the PDH lock at the level of $4 \times 10^{-13}/\sqrt{\rm Hz}$ as the orientation modulation and alignment control, in conjunction with the use of counterpropagating modes, has eliminated environmental effects. It should be noted that this is the first realization of an asymmetric optical resonator and conservative mirror selection led to a poorly impedance matched resonator. Mirrors with higher reflectivity and lower losses would increase the finesse and lead to an improved frequency lock, as would a higher PDH modulation frequency. This would give a corresponding improvement in performance of the experiment and the sensitivity to the SME parameters.

Conclusion.—A spatially modulated asymmetric resonator was used to constrain the isotropic shift of the speed of light, associated with our motion relative to the sun-centered reference frame and represented in the SME by the parameter $\tilde{\kappa}_{\rm tr}$. This parameter has been shown to be below $3 \pm 11 \times 10^{-10}$, a factor of 6 improvement on previous results from a stationary resonator. By rotating the resonator 180° every 617 seconds, the signal for LI violation is reversed while most systematic effects are not. This enables the isolation of LI signals from sidereal systematic effects, while alignment and intensity control suppress systematic effects associated with the rotation of the resonator leading to a reduction in the uncertainty of the experiment. We have utilized the concept of counterpropagating modes in an asymmetric ring resonator which again eliminates many systematic effects. There are significant improvements that can be made to future odd-parity experiments, and the techniques outlined here provide the impetus to vastly improve the constraints on odd-parity and isotropic violations of LI, and this experiment presents a method to enhance the sensitivity to these odd-parity experiments.

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[1] J. Alfaro, H. A. Morales-Técotl, and L. F. Urrutia, Phys. Rev. D **66**, 124006 (2002).
[2] J. D. Bjorken, Phys. Rev. D **67**, 043508 (2003).
[3] V. A. Kostelecký and S. Samuel, Phys. Rev. D **39**, 683 (1989).
[4] V. A. Kostelecký and R. Potting, Nucl. Phys. **B359**, 545 (1991).
[5] R. Mansouri and R. Sexl, Gen. Relativ. Gravit. **8**, 497 (1977).
[6] R. Mansouri and R. Sexl, Gen. Relativ. Gravit. **8**, 515 (1977).
[7] D. Colladay and V. A. Kostelecký, Phys. Rev. D **58**, 116002 (1998).
[8] D. Colladay and V. A. Kostelecký, Phys. Rev. D **55**, 6760 (1997).
[9] V. A. Kostelecký and M. Mewes, Phys. Rev. D **80**, 015020 (2009).
[10] S. R. Parker, M. Mewes, P. L. Stanwix, and M. E. Tobar, Phys. Rev. Lett. **106**, 180401 (2011).
[11] V. A. Kostelecký and M. Mewes, Phys. Rev. D **66**, 056005 (2002).
[12] S. Herrmann, A. Senger, K. Möhle, M. Nagel, E. V. Kovalchuk, and A. Peters, Phys. Rev. D **80**, 105011 (2009).
[13] C. Eisele, A. Y. Nevsky, and S. Schiller, Phys. Rev. Lett. **103**, 090401 (2009).
[14] M. A. Hohensee, P. L. Stanwix, M. E. Tobar, S. R. Parker, D. F. Phillips, and R. L. Walsworth, Phys. Rev. D **82**, 076001 (2010).
[15] M. E. Tobar, P. Wolf, A. Fowler, and J. G. Hartnett, Phys. Rev. D **71**, 025004 (2005).
[16] F. R. Klinkhamer and M. Schreck, Phys. Rev. D **78**, 085026 (2008).
[17] M. A. Hohensee, R. Lehnert, D. F. Phillips, and R. L. Walsworth, Phys. Rev. Lett. **102**, 170402 (2009).
[18] B. Altschul, Phys. Rev. D **80**, 091901 (2009).
[19] V. A. Kostelecký and N. Russell, Rev. Mod. Phys. **83**, 11 (2011).
[20] S. Reinhardt, G. Saathoff, H. Buhr, L. A. Carlson, A. Wolf, D. Schwalm, S. Karpuk, C. Novotny, G. Huber, M. Zimmermann, R. Holzwarth, T. Udem, T. W. Hansch, and G. Gwinner, Nature Phys. **3**, 861 (2007).
[21] G. Saathoff, S. Karpuk, U. Eisenbarth, G. Huber, S. Krohn, R. Muñoz Horta, S. Reinhardt, D. Schwalm, A. Wolf, and G. Gwinner, Phys. Rev. Lett. **91**, 190403 (2003).

[22] M. E. Tobar, E. N. Ivanov, P. L. Stanwix, J.-M. G. le Floch, and J. G. Hartnett, Phys. Rev. D **80**, 125024 (2009).

[23] F. N. Baynes, A. N. Luiten, and M. E. Tobar, Phys. Rev. D **84**, 081101 (2011).

[24] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Appl. Phys. B **31**, 97 (1983).

[25] E. A. Donley, T. P. Heavner, F. Levi, M. O. Tataw, and S. R. Jefferts, Rev. Sci. Instrum. **76**, 063112 (2005).

[26] S. T. Dawkins and A. N. Luiten, Appl. Opt. **47**, 1239 (2008).

[27] P. L. Stanwix, M. E. Tobar, P. Wolf, M. Susli, C. R. Locke, E. N. Ivanov, J. Winterflood, and F. van Kann, Phys. Rev. Lett. **95**, 040404 (2005).