

A New Method to Measure the Distance Between Graduation Lines on Graduated Scales

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Abstract—Line scales are used throughout industry for a variety of applications. The most common is the stage micrometer, a small, graduated glass scale for the calibration of optical instruments such as microscopes. However, stage micrometers are generally *not* calibrated, except for critical applications, due to the time and cost of optical calibration techniques. A method for calibrating line scales is presented which uses electrical test structure metrology. A description of the technique as well as examples of results from this technique are presented.

Index Terms—Electrical calibration, electrical test structure, laser interferometry, length, line scale, measurement uncertainty, optical calibration, scale graduations, stage micrometer, potentiometer, voltage-dividing.

I. INTRODUCTION

LINE SCALES in common use in industry include those with graduation pitch as small as $0.5\ \mu\text{m}$ to those as long as 1 m. These scales are either linearly or, more rarely, logarithmically graduated. Smaller scales are made from glass or quartz substrates; longer scales are made from steel, invar, glass, quartz, or Zerodur [1] substrates. The best quality 1-mm stage micrometers are produced using photolithographic etching of chromium on a glass or quartz substrate.

Presently, line scales are measured either by an optical comparator (for low accuracy) or by laser interferometry (for high accuracy). For a typical 1-mm stage micrometer, the spacings of the major subdivisions ($100\ \mu\text{m}$ nominal) are measured as well as the spacings of a single group of minor subdivisions ($10\ \mu\text{m}$ nominal). This calibration procedure is time consuming and, consequently, expensive. A simple, low-cost, *electrical test structure-based* calibration procedure for these line scales is described in this paper. Results of this calibration are compared with high-accuracy, laser-interferometry-based calculations.

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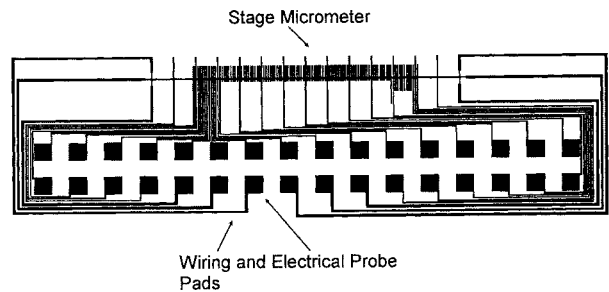


Fig. 1. The 1-mm NIST 20-stage micrometer.

II. CALIBRATION PROCEDURE

A. Test Structure

A 1-mm stage micrometer, designated NIST20 (Fig. 1), was designed for optical and electrical calibration. The electrical calibration technique is based on the modified voltage-dividing potentiometer [2] test structure, originally developed for VLSI lithography characterization. Fig. 2 highlights the key features of the NIST20 stage micrometer:

- 1) a horizontal bridge resistor;
- 2) voltage taps attached to selected graduations;
- 3) reference features (for analysis of the electrical measurements);
- 4) Van der Pauw crosses [3] to evaluate the uniformity of the conducting film.

The NIST20 stage micrometer was patterned at 10X, with e-beam lithography, in chrome on a quartz substrate. This 10X master was stepped across a second chrome-on-quartz substrate to produce the final 1X features.

B. Laser Interferometric Calibration

The NIST20 stage micrometer was measured by the NIST line scale interferometer (LSI) [4]. The NIST LSI consists of a scanning electro-optical line detector, a high precision one-axis motion system, and a high accuracy heterodyne interferometer for determining the displacement of the scale beneath the line detector. The wavelength of a stabilized helium–neon laser, corrected for temperature, relative humidity, and atmospheric pressure, is used as the length standard. The instrument is housed in an environmental chamber in which all environmental properties are carefully monitored. The frequency of the commercial laser used for the interferometer is calibrated

against the NIST's iodine stabilized helium–neon laser as a frequency standard. The iodine stabilized helium–neon laser has a wavelength $\lambda = 0.632\,991\,398\,22\,\mu\text{m}$ with an estimated relative standard uncertainty of 3.165×10^{-11} (1 σ) [5]. The wavelength of the light is computed from the vacuum wavelength of the iodine stabilized helium–neon laser and the index of refraction of the air along the light paths.

Each length value is the mean of eight measurements and the expanded standard uncertainty (U) for each value is

$$U = ku_c \quad (1)$$

where the combined standard uncertainty (u_c) is

$$u_c = \sqrt{(u_i^2 + u_j^2)} \quad (2)$$

where u_i is the standard uncertainty arising from random effects and u_j is the standard uncertainty arising from systematic effects in the measurement process. The coverage factor $k = 2$ was used which gives for each measured value a level of confidence of approximately 95% [6]. Measurements were made from line center to line center by scanning a 0.08 mm long segment of each line midway between the graduation line tips and the horizontal base line.

All lengths are reported at a temperature of 20 °C (68°F). During the measurement the instrument and the scale temperature was held at 20 ± 0.005 °C, and the scale length was normalized to 20 °C using the coefficient of linear thermal expansion of the quartz substrate ($0.5 \times 10^{-6}/^\circ\text{C}$). The measurements reported by the NIST LSI are all referenced to the 0.0 mm graduation line. Using this technique, this system is capable of routinely providing line spacing measurements with an expanded standard uncertainty of 10 nm for line spacings up to 100 mm.

The time required to calibrate a scale, using the NIST LSI technique, is determined mainly by the setup time and the calibration time. Setup time needed for a scale in normal position includes scale inspection and preparation, scale supporting, scale alignment and focusing under the microscope, laser interferometer alignment, and instrument, and scale temperature stabilization. When the scale is placed in the reverse position the setup time is reduced to the time needed for scale alignment and focusing and instrument and scale temperature stabilization. The actual calibration for a stage micrometer, with 40 intervals, requires three hours, while the scale setup requires four and one half hours. It is clear that using the NIST LSI multipurpose, one-dimensional measuring instrument, which has a measuring range of 1 μ to 1 m, requires considerable setup time. But a small dedicated LSI used only for measuring stage micrometers would enable the setup time to be reduced by at least a factor of two. In the next section we describe an electrical calibration technique that considerably improves the total calibration time.

C. Proposed Electrical Calibration Technique

Electrical characterization is performed using a commercial parametric test system, with the following key features:

- 1) a low-noise switching matrix;
- 2) a high-linearity and accuracy (i.e., calibrated traceable to NIST) current source and microvolt meter.

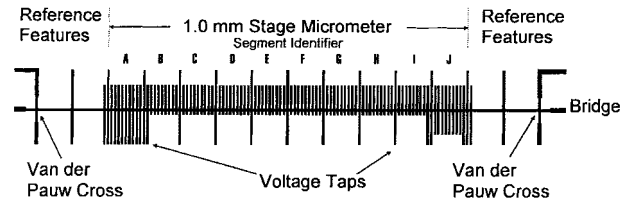


Fig. 2. The active area of the NIST 20 stage micrometer showing key features.

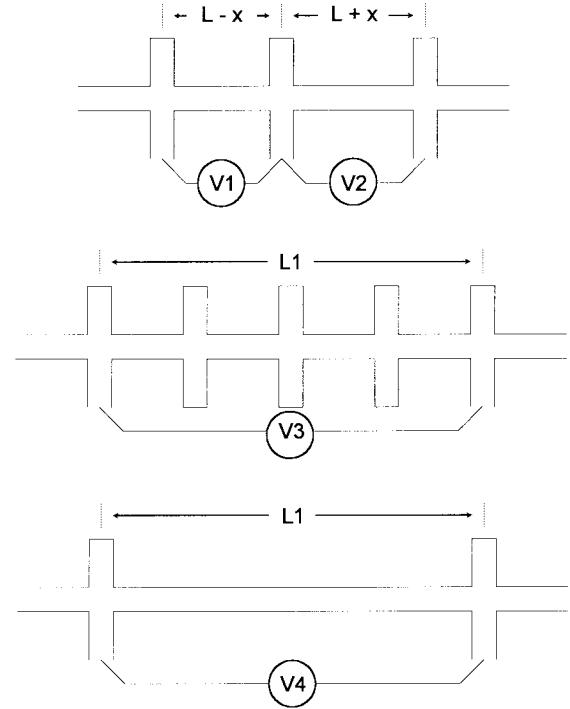


Fig. 3. Features of the modified voltage-dividing potentiometer.

Features of a generic potentiometer test structure are shown in Fig. 3. The displacement of the central tap from the midpoint of the end taps in Fig. 3(a) is given by

$$x = \left(\frac{V_1 - V_2}{V_1 + V_2} \right) \left(\frac{L_e}{2} \right) \quad (3)$$

where L_e is the electrical length of the bridge. The *electrical length* differs conceptually from the physical length, i.e., that which an instrument such as the line scale interferometer would measure. The electrical length is defined as the physical length that an ideal feature of a measured series resistance and known and uniform width and sheet resistance would exhibit. It differs from the physical length when, for example, there is current shunting due to the discontinuities at the voltage taps, as occurs in this type of structure. For the features shown in Fig. 3(a), the electrical length is

$$L_e = 2L - 2\delta L \quad (4)$$

where L is one-half of the physical length and δL is the net effect of a single voltage tap on the length. Since δL is dependent on the exact geometry of the intersection, it must be determined empirically. One method of determining δL uses

measurements of two additional features [Fig. 3(b) and (c)]. Here

$$\delta L = L_1 \left(\frac{V_4 - V_3}{(n+1)V_4 - V_3} \right) \quad (5)$$

where n is the number of “dummy taps” in Fig. 3(b).

Rather than the single, centered, interior tap of the generic structure, graduations within NIST20 are placed at 0.01 mm intervals along a 1-mm bridge in 10 major subdivisions of 10 segments each. A number of these graduations extend to probe pads for electrical measurement. Therefore an equation for x , more general than (3), was derived for arbitrary pairs of segments. The voltage drop along each segment, for a constant forced current, is proportional to the electrical length of the segment, i.e.,

$$V_l = k(L_l - \sum_l \delta L x) \quad (6)$$

and

$$V_r = k(L_r \sum_r \delta L + x) \quad (7)$$

where k depends on the sheet resistance and bridge width and therefore is constant within a single bridge. The subscripts l and r refer to the left- and right-hand segments, respectively. The L and δL terms are the lengths of the segments and the total change in physical length due to the intervening taps, respectively. Taking the ratio of these two equations and solving for x yields

$$x = \frac{V_r \left(L_l \sum_l \delta L \right) - V_l \left(L_r \sum_r \delta L \right)}{V_l + V_r}. \quad (8)$$

Unlike in the generic structure, interior segments of the graduated scale were used, in conjunction with the reference features, to determine δL .

The sources of uncertainty in the electrical measurements of the placement of the graduations were determined. The relative impacts of these factors are different for features of substantially different spacings. For the 0.01 mm spaced graduations, the uncertainty in the reference length [i.e., $L_l + L_r$ in (8); assumed to be the design value] is dominant. Since the reference length uncertainty is constant within a single bridge, the effect will be less when finding the placements of the 0.10-mm spaced graduations. For the 0.10-mm spaced graduations, the primary source of uncertainty is due to instrumentation. The reason for this can be seen by considering of (8). Since x is approximately zero, the terms in the numerator are approximately equal. Thus, for increased resistances the difference between the two terms as a percentage of the terms is smaller. This becomes the classic problem of accurately determining the small difference between two large measurements where the uncertainty of the instruments is a percentage of the measurement range and/or measured value. Additional sources of uncertainty in the electrical measurement are bridge nonuniformities and variations in δL .

During electrical testing, the temperature was approximately 23°C. A typical time for electrical characterization of the

TABLE I
CALCULATED δL 's AND STANDARD DEVIATION (σ)

Tap Type	Number of Segments	δL (μm)	σ (μm)
Isolated	2	0.973	0.051
End (long extensions)	2	1.329	0.004
Transition	2	1.356	0.006
Interior	6	1.375	0.005

NIST20 stage micrometer is six minutes and the repeatability of electrical feature placement measurements, is approximately 0.8 nm (2σ), where σ is the average of repeated measurements.

III. RESULTS

A. Length-Effect Parameter Calculation

Analysis of the measurements showed that there was a large difference in the length effects of isolated voltage taps and interior voltage taps. Additionally, there were small differences between different groups of ten taps along the stage micrometer; in particular, between the end graduations (segments A and J in Fig. 2), transition graduations (segments B and I), and interior graduations (segments C–H). The different values for the δL 's are shown in Table I. These differences were too large to be explained by either the graduation placement error (see the calibration results in the next section) or nonuniformities in the sheet resistance (which was uniform and measured to be 18.9 Ω/\square) and are likely due to lithographic proximity effects.

B. Stage Micrometer Calibrations

Results from optical (line scale interferometer) and electrical calibration of a NIST20 stage micrometer are shown in Table II. The optical measurements, which provide a baseline for comparison with the proposed electrical technique, show the graduations were generally placed close to the design values. Comparison of the differences in measured graduation placement between the two techniques provides an estimate of the uncertainty in the electrical measurements. The average differences are 0.009 and 0.028 μm for the 0.01- and the 0.1-mm-spaced features, respectively.

IV. NEW DESIGN

It is likely that an enhanced design would reduce the measured differences between the optical and electrical measurements by reducing the variation in δL , due to lithographic proximity effects. Two modifications to the design shown in Fig. 2 are foreseen: first, extending the taps that extend a short distance below the bridge in Fig. 2 and second, placing one or more additional 0.1 μm segments of ten graduations, which would not be used in the measurement, at each end of the stage micrometer. An additional enhancement would be to widen the bridge to lower the bridge resistance, thereby reducing the combined uncertainty in the measurements of the 0.10-mm-spaced segments.

TABLE II
GRADUATION SPACINGS IN THE NIST20 STAGE MICROMETER

Line Pitch (Interval from 0.000 μm)	Line Scale Interferometer		Voltage-Dividing Potentiometer	
	Length (μm)	Expanded Uncertainty (μm)	Length (μm)	Difference (μm)
10.000	10.005	0.004	10.004	0.001
20.000	20.004	0.004	20.011	-0.007
30.000	30.005	0.008	30.037	-0.032
40.000	40.005	0.008	40.019	-0.014
50.000	50.003	0.008	50.006	-0.003
60.000	59.997	0.006	60.014	-0.017
70.000	69.997	0.006	70.008	-0.011
80.000	79.997	0.004	80.013	-0.016
90.000	89.996	0.006	90.010	-0.014
100.000	99.997	0.006	99.971	0.026
200.000	200.001	0.008	200.030	-0.029
300.000	300.003	0.008	300.002	0.001
400.000	400.004	0.006	399.965	0.039
500.000	499.999	0.008	499.947	0.052
600.000	600.006	0.004	600.019	-0.013
700.000	700.003	0.008	699.978	0.025
800.000	800.003	0.006	800.030	-0.027
900.000	900.007	0.004	899.971	0.036
1000.000	1000.006	0.006	Reference Length (Electrical)	

V. CONCLUSIONS

The electrical metrology technique potentially provides quick and inexpensive calibrations of stage micrometers. While the accuracy provided by the line scale interferometer, a primary calibration system in a national standards laboratory, exceeds that provided by electrical test structure metrology, the accuracy provided by electrical test structure metrology likely exceeds the requirements of most applications and it has the benefit of using widely available commercial instrumentation. Thus, the electrical technique would be ideal for providing the general user access to inexpensive, calibrated artifacts.

The results of this experiment also suggest that an alternative process for production of graduated scales may lead to much more accurate feature placement. In particular, adoption of the VLSI production techniques (electron-beam lithography followed by photoreduction) may lead to extremely accurate graduated scales requiring minimal calibration for common applications.

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