Atomic Microwave Power Standard Based on the Rabi Frequency

Moto Kinoshita, Kazuhiro Shimaoka, and Koji Komiyama

***Abstract*—The Rabi frequency for an atomic hyperfine structure transition is proportional to the magnetic field strength of the incident electromagnetic wave. Using the known proportionality constant, an atomic microwave power standard based on the Rabi frequency can be realized. In this paper, the Rabi frequency of cesium atoms in a glass cell inserted in a microwave waveguide was measured using the atomic-candle method. The Rabi frequency was converted into the incident microwave power via the magnetic field strength by correcting the effects of the glass cell and impedance mismatch. The relative expanded uncertainty was approximately 4% at a coverage factor of 2. The microwave power measured from the Rabi frequency was compared with that measured by a calorimetric method. These results coincided within their uncertainties.**

***Index Terms*—Atom optics, atomic measurements, frequency measurement, measurement standards, metrology, microwave measurements, microwave sensors, power measurement.**

I. Introduction

OVER THE PAST several decades, microwave power has mainly been measured by calorimetric and bolometric methods. In fact, most national metrology laboratories have adopted these methods for the microwave power standard. On the other hand, a new method of measuring the microwave power based on the Rabi frequency has recently attracted attention [1], [2]. This method is expected to be applied in an atomic microwave power standard.

The Rabi frequency for an atomic hyperfine structure transition is proportional to the magnetic field strength of the incident microwave. The proportionality constant depends on physical constants and the quantum properties of the atomic structure. The proportional relationship between the Rabi frequency Ω and the magnetic field strength of the incident microwave H is

$$\Omega = \frac{\mu_0 \mu_B g_J \langle F', m_{F'} | J | F, m_F \rangle}{\hbar} H \tag{1}$$

where μ_0 is the magnetic permeability, μ_B is the Bohr magneton, g_J is the Landé g-factor, $\langle F', m_{F'} | J | F, m_F \rangle$ is the matrix element of the electron angular momentum, and $\hbar$ is the reduced Planck's constant. These values have been empirically or theoretically verified so accurately that the magnetic field strength of a microwave can be obtained by measuring the Rabi frequency.

There are various methods of measuring the Rabi frequency, involving the use of a glass cell, laser-cooled atoms, or a beam of atoms. Methods using laser-cooled atoms and a beam of atoms require complicated instruments. This is disadvantageous, because the impedance mismatch of the transmission line caused by such complicated instruments affects the estimation of the microwave power. Very few analyses of the impedance of a transmission line in which a microwave and atoms interact have been previously reported. On the other hand, the method using vapor atoms in a glass cell is generally so simple and practical that the effect of impedance mismatch can be reduced or corrected. Therefore, we have investigated the Rabi frequency generated by the interaction between ^{133}Cs atoms in a glass cell inserted in a WR90 waveguide and a resonant microwave. This is because an industrially used waveguide such as WR90 enables us to analyze the impedance mismatch and the distribution of magnetic field strength.

We demonstrated the measurement of the magnetic field strength of a microwave using the Rabi frequency in previous studies [3], [4]. We then reported the measurement of absolute microwave power from the Rabi frequency of Cs atoms [5]. In this paper, we expand the report by comparing the microwave power measured using the Rabi frequency with that obtained by the calorimetric method and detailing the evaluation of the measurement uncertainties.

II. Theory

The most difficult point in the observation of the Rabi frequency is the inhomogeneity of the incoherent atoms in the glass cell. Camparo et al. proposed the atomic-candle method, which enables the observation of the Rabi frequency of vapor atoms in a glass cell and stabilizes the microwave intensity [6], [7]. The atomic-candle method is described as follows. Upon irradiating the atoms in a glass cell with a resonant laser and a resonant microwave simultaneously, a double resonance spectrum appears upon laser absorption. Then phase modulation is applied to the microwave. According to a calculation based on the density matrix equation between two-level atoms and the phase-modulated resonant microwave [8], a microwave with phase modulation at a frequency of ω_m and an amplitude of

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θ_m induces a parametric oscillation at a harmonic frequency of $2\omega_m$. The amplitude of the parametric oscillation A_2 is

$$A_2 \propto \frac{\theta_m^2 \omega_m \Omega^2 \gamma_1 (\gamma_1 \gamma_2 + \Omega^2)^{-1}}{\sqrt{(\Omega^2 - 4\omega_m^2)^2 + 4\gamma_1^2 \omega_m^2}} \tag{2}$$

where γ_1 is the longitudinal relaxation and γ_2 is the transverse relaxation. Equation (2) shows that the Rabi frequency Ω can be obtained as twice the frequency of the phase modulation ($\Omega = 2\omega_m$) when the amplitude A_2 is maximum, under the condition of $\gamma_1\gamma_2 \ll \omega_m^2$.

Microwave power measurement based on the Rabi frequency has the following advantages over the calorimetric method: 1) It is more stable; the new method depends on atomic characteristics, which are more stable than the electrical components comprising a calorimeter. 2) It is quicker than calorimetric measurement; the atomic system has a short time constant. 3) It enables remote calibration; two different microwave powers at a distance from each other can be compared in terms of frequency. In addition, a comparison between the new method and the calorimetric method enhances the reliability of both methods.

III. Experiment

In this experiment, the Rabi frequency of ^{133}Cs atoms was first measured. Second, the magnetic field strength of the microwave was estimated from the Rabi frequency. Third, the microwave power transmitted in the glass cell was calculated from the magnetic field strength. Finally, the microwave power entering the test port, defined as the plane immediately in front of the glass cell, was quantified.

The experimental setup to observe the atomic-candle-type Rabi resonance is shown in Fig. 1. The glass cell, which contains ^{133}Cs at the saturated vapor pressure and N_2 buffer gas at a pressure of 1.3 kPa, was inserted into a WR90 waveguide. The glass cell was designed to snugly fit inside the waveguide. A microwave with a frequency of approximately 9.2 GHz from a signal generator and a laser with a wavelength of 852 nm, which resonates with the $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}$ transition, from an external cavity diode laser (ECDL) were guided into the Cs cell. The standing microwave generated by multiple reflections in the glass cell was removed using a tuner and isolators. This is very important in determining a unique value of the Rabi frequency, because the standing wave generates a nonuniform microwave field strength, i.e., a locally varying Rabi frequency, in the glass cell. The diameter of the laser beam was adjusted to 6 mm using an optical aperture. The laser intensity, which affects the longitudinal relaxation γ_1 and the signal-to-noise ratio (SNR), was adjusted to 100 μW/cm^2 using a neutral density (ND) filter before entering the waveguide. A laser intensity of as low as 100 μW/cm^2 provides the best ratio of the SNR to γ_1 and has little effect on the measured value of the Rabi frequency in this experiment. The laser beam passed through the hollow waveguide system and the transparent glass cell and was detected by a photodetector (PD). The microwave-optical double resonance spectrum was obtained from the output voltage of the PD. A DC magnetic

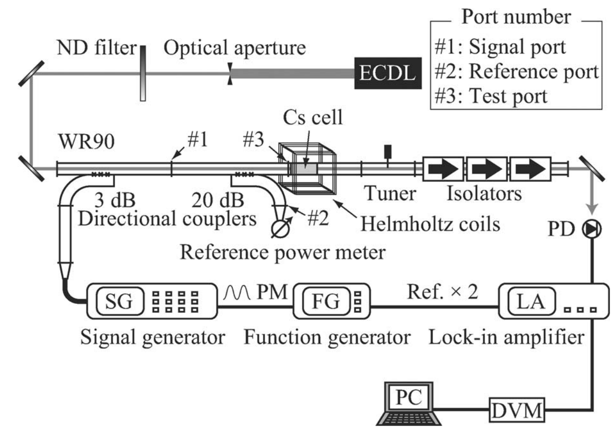

Fig. 1. Experimental setup. The microwave with a frequency of 9.2 GHz and the laser with a wavelength of 852 nm were simultaneously introduced into the Cs cell. The atomic-candle-type spectrum was obtained from the output voltage of a lock-in amplifier.

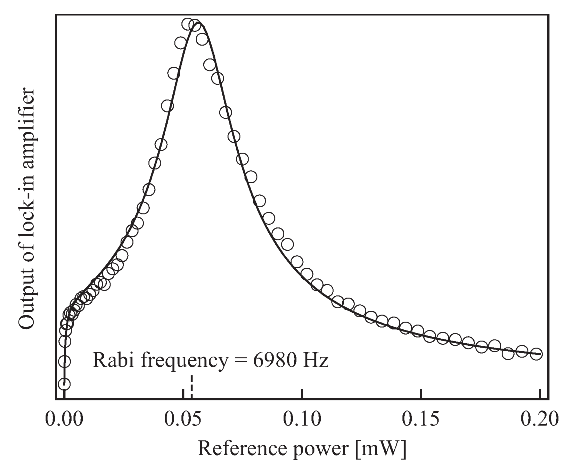

Fig. 2. Atomic-candle-type spectrum. The circles are the output of the lock-in amplifier. The solid line is fitted using (2). The frequency of the phase modulation, $\omega_m/2\pi$, was 3490 Hz. The peak position (broken line on the horizontal axis) of this spectrum links the reference power of 0.054 mW to the Rabi frequency of 6980 Hz.

field with a magnetic flux density of 35 μT generated by three pairs of Helmholtz coils defines the quantization axis as the x-axis, which is parallel to the longer sides of the rectangular waveguide. Then the microwave frequency was locked on the $|F = 3, m_F = 0\rangle \rightarrow |F = 4, m_F = 0\rangle$ hyperfine transition in the ground state, which is 9.1926413 GHz in this experiment because of the N_2-buffer-gas shift [9].

Here, a sinusoidal phase modulation (PM) with an amplitude θ_m of 2.0 rad was applied to the microwave using a function generator. Consequently, the phase modulation induced the second harmonic of the microwave-optical double resonance spectrum, whose amplitude is known from (2). This second harmonic was detected by a lock-in amplifier, which was synchronized with twice the frequency of the phase modulation. By scanning the microwave power, which was sampled as the reference power using a 20 dB directional coupler and a reference power meter, the atomic-candle-type spectrum was obtained as shown in Fig. 2. Here, the frequency of the phase modulation, $\omega_m/2\pi$, was 3490 Hz. Thus, the Rabi frequency, $\Omega/2\pi$, was 6980 Hz at the maximum point in the

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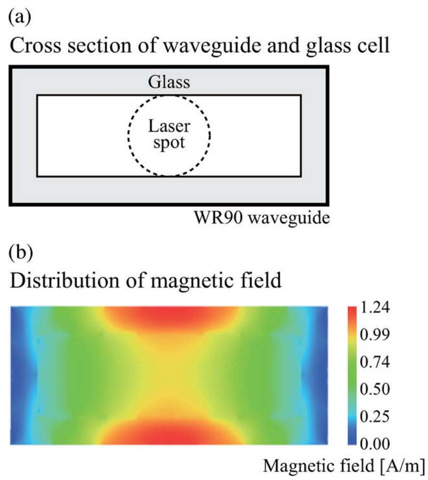

Fig. 3. Cross section of the waveguide and the glass cell (a) and calculated distribution of the magnetic field component parallel to the x-axis (b). In the calculation, the microwave power transmitted across the cross section is 24.6 mW. The conversion factor α is evaluated as the ratio of the transmitted power to the square of the magnetic field component at the center of the waveguide.

atomic-candle-type spectrum. The slight discrepancy between the output of the lock-in amplifier (circles) and the fitted curve (solid line) in Fig. 2 probably arises from small inaccuracies in (2) such as in the spatial distribution of the microwave field [8]. Consequently, the peak of the atomic-candle-type spectrum was estimated as the zero crossing of the differentiated output of the lock-in amplifier using an interpolation method. The peak position links the reference power of 0.054 mW to the Rabi frequency of 6980 Hz. Atomic-candle-type spectra at various frequencies of the phase modulation, $\omega_m/2\pi$, from 2240 Hz to 10.41 kHz were also obtained and the corresponding Rabi frequencies were measured successively at the peak of each spectrum.

IV. Discussion

A. Absolute Power Evaluation

By substituting the Rabi frequency measured above for Ω in (1), the magnetic field component parallel to the x-axis of the microwave, denoted H_x, was calculated. To estimate the microwave power transmitted in the waveguide from the magnetic field component obtained above, the relation between them is required. However, it is difficult to analytically obtain an exact solution for the distribution of the magnetic field. Therefore, we performed a simulation to evaluate the conversion factor α, defined as the ratio of the microwave power transmitted in the waveguide to the square of the magnetic field component at the center of the waveguide, using a 3-D electromagnetic simulator [10]. Fig. 3 shows the cross section of the waveguide and the glass cell Fig. 3(a) and the calculated distribution of the magnetic field component parallel to the x-axis Fig. 3(b). The distribution of the magnetic field was obtained when the power transmitted across the cross section is 24.6 mW.

Finally, the microwave power entering the test port P_{Rabi} is quantified by correcting the impedance mismatch at the test port. The impedance mismatch is transposed in terms of the

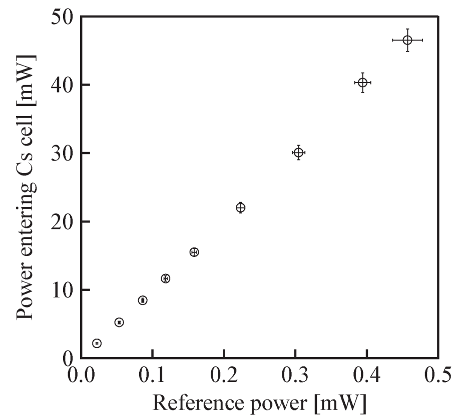

Fig. 4. Dependence of the microwave power entering the test port on the reference power. The microwave power entering the test port was obtained from the measured Rabi frequency. The reference power was the power indicated by the reference power meter when the atomic-candle-type spectrum was maximum. The error bars of both axes represent the expanded uncertainties when $k = 2$.

complex reflection coefficient of the waveguide containing the glass cell Γ_r. Therefore, P_{Rabi} is written as

$$P_{Rabi} = \frac{\alpha H_x^2}{1 - |\Gamma_r|^2}. \quad (3)$$

The microwave power entering the test port P_{Rabi} based on the Rabi frequency was obtained from (3) and its dependence on the reference power R_{Rabi}, which was the power indicated by the reference power meter when the atomic-candle-type spectrum was maximum, is shown in Fig. 4. The slope of the line in Fig. 4 was estimated to be 100.8 $\pm$ 0.6 by the least-squares method. The error bars in the longitudinal and horizontal directions represent the expanded uncertainties at a coverage factor k of 2, the value by which the combined standard uncertainty was multiplied to obtain an expanded uncertainty. The evaluation of the uncertainties is explained in Section IV-C.

B. Comparison

Next, the microwave power entering the test port was measured by a calorimetric power meter and compared with that obtained above from the Rabi frequency. The power meter was calibrated by the 7 mm coaxial calorimeter used for the primary standard at NMIJ. Although the calorimeter provides the 7 mm coaxial power meter with the calibration factor K_{calo}, the test port has a WR90 waveguide. Using a PC-7 coaxial with the WR90 waveguide adapter, whose efficiency η was measured by a vector network analyzer, the 7 mm coaxial power meter was connected to the test port. Therefore, the microwave power entering the test port P_{calo} is written as

$$P_{calo} = \frac{P_{ind}}{\eta K_{calo}} \quad (4)$$

where P_{ind} is the value indicated by the power meter.

The waveguide with the Cs cell and the calorimetric power meter were alternately connected to the test port. Then the ratio of the power entering the test port to that entering the reference

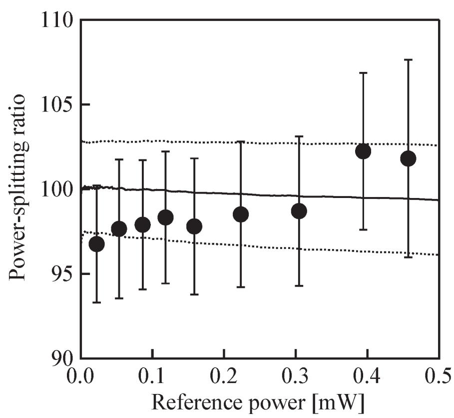

Fig. 5. Comparison between microwave power measurements based on the Rabi frequency and on the calorimeter. The circles and solid line represent the power-splitting ratios measured from the Rabi frequency and the calorimetric power meter, respectively. The dotted lines represent the expanded uncertainty of the calorimetric measurement when $k = 2$. Both values coincided within their uncertainties.

port was measured for each setup. Here, the following equation must theoretically hold between both measured values:

$$\frac{P_{Rabi}}{R_{Rabi}} = \frac{P_{calo}}{R_{calo}} \left| \frac{1 - \Gamma_{ge}\Gamma_c}{1 - \Gamma_{ge}\Gamma_r} \right|^2 \tag{5}$$

where R_{calo} is the value indicated by the reference power meter when P_{calo} is measured. Γ_c is the complex reflection coefficient of the calorimetric power meter. Γ_{ge} is the equivalent reflection coefficient of the signal source, where

$$\Gamma_{ge} = S_{33} - \frac{S_{31}S_{23}}{S_{21}} \tag{6}$$

for the scattering parameters S_{ij} of the 20 dB directional coupler. The port numbers are defined in Fig. 1. The complex reflection coefficient Γ_c, Γ_r, and the scattering parameters S_{ij} were measured by a vector network analyzer.

Fig. 5 shows a comparison between the microwave power measurements based on the Rabi frequency and the calorimeter. The circles represent the power-splitting ratio based on the Rabi frequency, i.e., the left-hand side of (5). The solid line represents the power-splitting ratio measured by the calorimetric power meter, i.e., the right-hand side of (5). The dotted lines represent the expanded measurement uncertainty of the calorimetric measurement with a coverage factor k of 2, which is explained in Section IV-C. Both ratios were approximately 100, which agrees with the fact that the directivity of the directional coupler was 20 dB. The relative difference between the ratios was typically less than 3%, which is less than their uncertainties. The degree of agreement was less than 0.8 in terms of the E_n value, defined as

$$E_n = \frac{|x_1 - x_2|}{\sqrt{U^2(x_1) + U^2(x_2)}} \tag{7}$$

where x_1 and x_2 are the left-hand side and right-hand side of (5), respectively, and $U(x_1)$ and $U(x_2)$ are their uncertainties, which are detailed in Section IV-C. Therefore, microwave power measurement based on the Rabi frequency is consistent with that based on a calorimeter.

C. Uncertainty

The relative expanded uncertainty [11] of the microwave power P_{Rabi}, R_{Rabi}, and the right-hand side of (5) measured above were adopted in Figs. 4 and 5 and (7) with a coverage factor k of 2. The evaluation of these uncertainties is described as follows.

The uncertainty budget concerning P_{Rabi} and R_{Rabi} at the Rabi frequency of 10.42 kHz, which corresponds to 0.119 mW in terms of the reference power, is shown in Table I. The converted relative uncertainty in Table I and what follows is defined as the ratio of the measurement uncertainty multiplied by the sensitivity coefficient between the measurand and each component to the measurand value. Each component is described as follows.

Peak finding: The component of the peak finding was obtained from the uncertainty of the peak of the atomic-candle-type spectrum. The converted relative uncertainty was 0.15%.

Nonlinearity: The component of the nonlinearity was the nonlinearity of the reference power meter. The nonlinearity was evaluated by comparison with that of fixed attenuators. The converted relative uncertainty was 0.92%.

Dispersion: The dispersion was the standard deviation of the mean of the three measurements taken. The converted relative uncertainty was 0.08%.

The expanded measurement uncertainty was calculated as the root sum square of each component value. That of R_{Rabi} was 1.9% at the coverage factor k of 2.

Magnetic field strength: The component of the magnetic field strength was obtained from the uncertainty of the frequency of phase modulation and the proportionality constant in (1). The converted relative uncertainty of the frequency was less than 0.0006%, and that of the proportionality constant in (1) was 0.00001%. Because their combined value was approximately 0.0006%, which is much less than that of other components, it was neglected.

Conversion factor α: The component of the conversion factor α consisted of the dispersion attributed to the laser spot, the modeling error including the dielectric constant of the glass and the size of the waveguide and glass cell, and the accuracy of the numerical calculations. The converted relative uncertainty of the dispersion attributed to the laser spot was 0.67%, that of the modeling error including the dielectric constant and the waveguide and glass cell size was 1.18%, and that of the accuracy of the numerical calculations was 0.91%. Their combined value was 1.64%, which is the dominant component in the measurement of microwave power based on the Rabi frequency.

Reflection coefficient: The component of the reflection coefficient was estimated from the uncertainty of the vector network analyzer with which Γ_r was measured. The converted relative uncertainty was 0.60%.

The expanded measurement uncertainty of P_{Rabi} was 3.5% at the coverage factor k of 2.

The relative uncertainty of the power-splitting ratio between the microwave power entering the test port P_{Rabi} and the reference power R_{Rabi} was calculated as the root sum square of the relative uncertainties of P_{Rabi} and R_{Rabi}. The relative

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TABLE I
UNCERTAINTY BUDGET OF P_{Rabi} AND R_{Rabi} WHEN $\Omega/2\pi$ IS 10.42 kHz. THE COMPONENTS OF THE RELATIVE UNCERTAINTY AND THEIR VALUES ARE INDICATED. THE CONVERTED RELATIVE UNCERTAINTY IS THE RATIO OF THE MEASUREMENT UNCERTAINTY MULTIPLIED BY THE SENSITIVITY COEFFICIENT TO THE MEASURAND VALUE

Measurand	Component	Converted relative uncertainty
P_{Rabi}	Peak finding	0.15 %
	Nonlinearity	0.92 %
	Dispersion	0.08 %
	Total (k = 1)	0.9 %
	Total (k = 2)	1.9 %
R_{Rabi}	Magnetic field strength	negligible
	Conversion factor α	1.64 %
	Reflection coefficient	0.60 %
	Total (k = 1)	1.7 %
	Total (k = 2)	3.5 %
$\frac{P_{Rabi}}{R_{Rabi}}$	Total (k = 1)	2.0 %
	Total (k = 2)	4.0 %

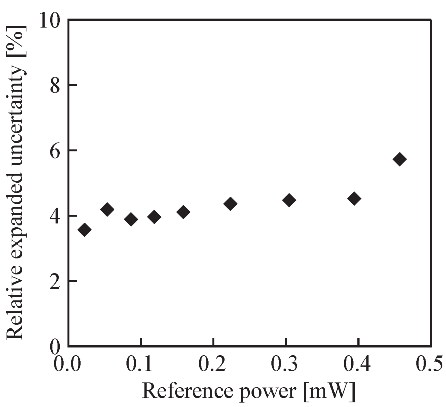

Fig. 6. . Relative expanded uncertainty of the power-splitting ratio between P_{Rabi} and R_{Rabi} as a function of the reference power. The coverage factor k is 2.

expanded uncertainties at the coverage factor k of 2 as a function of the reference power are shown in Fig. 6. The typical value of uncertainty was approximately 4%.

The uncertainty budget of the right-hand side of (5) at the reference power of 0.119 mW is shown in Table II. Each component is described as follows.

Calibration factor: The component of the calibration factor was obtained from the uncertainty of calibration by the primary standard at NMIJ [12]. The converted relative uncertainty was 0.20%.

Adapter efficiency: The component of the adapter efficiency was estimated from the uncertainty of the vector network analyzer, which adopted the two-port calibration of a PC-7 coaxial and a WR90 waveguide. The converted relative uncertainty was 1.15%, which is the dominant component in the calorimetric measurement of microwave power.

Reflection coefficient: The component of the reflection coefficient was obtained as a combination of the uncertainties of Γ_c and Γ_{ge}. The uncertainty of Γ_{ge} was also obtained by combining the uncertainties of the scattering parameters S_{ij}. These values were estimated from the uncertainties of the vector network analyzer. The converted relative uncertainty of Γ_c was 0.51%, and that of Γ_{ge} was 0.29%. Thus, their combined value was 0.59%.

TABLE II
UNCERTAINTY BUDGET OF THE RIGHT-HAND SIDE OF (5) AT THE REFERENCE POWER OF 0.119 mW. THE COMPONENTS OF THE RELATIVE UNCERTAINTY AND THEIR VALUES ARE INDICATED

Component	Converted relative uncertainty
Calibration factor	0.20 %
Adapter efficiency	1.15 %
Reflection coefficient	0.59 %
Nonlinearity	0.59 %
Dispersion	0.25 %
Total (k = 1)	1.5 %
Total (k = 2)	2.9 %

Nonlinearity: The component of the nonlinearity was the relative nonlinearity between the reference power meter and the calorimetric power meter. The converted relative uncertainty was 0.59%.

Dispersion: The dispersion was the standard deviation of the mean of the three measurements taken. The converted relative uncertainty was 0.25%.

The expanded measurement uncertainty of the calorimetric measurement of the microwave power was 2.9% at the coverage factor k of 2.

V. CONCLUSION

In this paper, the Rabi frequency of ^{133}Cs in a glass cell was estimated from the frequency of the phase modulation applied to the microwave when the atomic-candle-type spectrum is maximum. The Rabi frequency was converted into the magnetic field strength of the microwave using the proportionality relation. The microwave power in the glass cell was obtained as the square of the magnetic field strength multiplied by the conversion factor. Then, the microwave power entering the test port was quantified through the correction of the complex reflection coefficient. In addition, the microwave power based on the Rabi frequency was compared with that measured by a calorimetric power meter.

To our knowledge, this work is the first example of measuring the absolute power of a microwave using the atomic-candle method and comparing it with the calorimetric measurement. The relative expanded uncertainty was approximately 4% at a coverage factor k of 2, which is the smallest value among the reported measurements of microwave power based on the Rabi frequency. The measurements of microwave power based on the Rabi frequency and the calorimeter coincided within their uncertainties. This is an important result, which demonstrates the feasibility of the new method of measurement and its use in an atomic microwave power standard.

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