Investigation and Improvement of Thermal Stability of a Chromatic Confocal Probe with a Mode-Locked Femtosecond Laser Source

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Abstract: An intentional investigation on the thermal stability of a mode-locked femtosecond laser chromatic confocal probe, which is a critical issue for the probe to be applied for long-term displacement measurement or surface profile measurement requiring long-time scanning, is carried out. At first, the thermal instability of the first prototype measurement setup is evaluated in experiments where the existence of a considerably large thermal instability is confirmed. Then the possible reasons for the thermal instability of the measurement setup are analyzed quantitatively, such as the thermal instability of the refractive index of the confocal lens and the thermal expansion of mechanical jigs employed in the probe. It is verified that most of the thermal instability of the measurement setup is caused by the thermal expansion of mechanical jigs in the probe. For the improvement of the thermal stability of the probe, it is necessary to employ a low thermal expansion material for the mechanical jigs in the measurement setup and to shorten the optical path length of the laser beam. Based on the analysis result, a second prototype probe is newly designed and constructed. The improved thermal stability of the second prototype probe is verified through theoretical calculations and experiments.

Keywords: chromatic confocal probe; thermal stability; measurement resolution; mode-locked femtosecond laser

1. Introduction

Confocal microscopes [1,2] are valuable instruments for non-contact surface profile measurement [3,4], and are employed in various scientific and industrial fields due to their principles that allow three-dimensional profile measurement in the ambient atmosphere. One of the main features of the confocal probe employed in a confocal microscope is a depth-sectioning effect that realizes a high resolution measurement in the axial direction by extracting a signal from the focal plane while excluding the unnecessary signals from the other planes [5]. In the case of a confocal probe employing a monochromatic light source [6–9], it is necessary to scan a target sample in the axial direction for obtaining an axial response; the maximum signal of the axial response is reached when the surface is exactly located on the focal plane of the objective lens in the confocal probe [9]. Meanwhile, in the case of a confocal probe employing a chromatic light source and a chromatic objective lens, which is often referred to as the chromatic confocal probe [9–12], the height information can be obtained by monitoring the light spectrum detected by the point detector in the confocal probe. In a chromatic confocal probe, the axial chromatism is used as a space-coding method, in which a different wavelength is associated with each point of the optical axis to provide a mathematical relationship between the surface height and the wavelength focused on the surface [9]; namely, the height information can be obtained without scanning the target in the axial direction. This characteristic allows the chromatic
confocal probe to reduce the influences of motion errors of the mechanical scan of a target sample. Conventional chromatic confocal probes employing a white light source such as a halogen lamp or an LED (light-emitting diode) have been achieved a sub-micrometric vertical resolution [13–16]. Meanwhile, instability and low spectral power density of such a white light source are issues to be addressed to achieve better performances.

In responding to the background described above, several types of chromatic confocal probes employing a super-continuum light source, which has a higher light intensity, better spatial coherence, and a wider spectral range, have been developed so far [17–20]. In addition, optical configurations with various dual-detector setups have been proposed to obtain axial responses in a better sensitivity [21–24]. The author’s group has also proposed a chromatic confocal probe with a new dual-detector setup and a mode-locked femtosecond laser source [24]. The proposed femtosecond laser chromatic confocal probe is designed to divide the reflected laser beam from a target sample surface into two beams and capture them by two identical fiber detectors of an optical spectrum analyzer. It should be noted that one of the divided beams is coupled into the fiber detector placed on the focal plane of a coupling lens, while the other beam is coupled into another fiber detector placed on the plane slightly shifted from the focal plane of another coupling lens; namely, the optical setup has two different confocal setups. By obtaining light spectra of the divided beams captured in the different confocal setups, the “normalized” spectrum, which can be employed as a highly-sensitive axial response, can be obtained [24]. Experimental results have demonstrated that the proposed method can realize a vertical resolution of 30 nm and a measurement range of 40 μm [24]. Furthermore, it has also been demonstrated that the measurement range can be expanded to 250 μm by utilizing side-lobes in the normalized spectrum [25].

On the other hand, since an optical spectrum analyzer is employed to read the spectra over a wide light wavelength range of 160 nm in the developed setup, it takes a relatively long time (8 s) to make the measurement at one height position of a target sample. The thermal stability of the probe is thus a critical issue when the developed probe is applied for long-term displacement measurement or surface profile measurement where long-time scanning is required. In this paper, experimental verification of the thermal stability of the first prototype femtosecond laser chromatic confocal probe [24] is carried out where a considerably large thermal instability of the probe for displacement measurement is verified. The possible reasons for the thermal instability of the probe, such as the thermal instability of the refractive index of the confocal lens and the thermal expansion of mechanical jigs of the probe, are then analyzed quantitatively. Based on the analysis results, a second prototype femtosecond laser chromatic confocal probe is newly designed and constructed to improve the thermal stability for displacement measurement where the optical path length of the laser beam is minimized and a low thermal expansion material is employed for mechanical jigs in the optical setup. Experimental results for demonstrating the improved thermal stability of the second prototype probe are also presented. It should be noted that the thermal stability of the overall chromatic confocal measurement setup is contributed by not only the thermal stability of the chromatic confocal probe itself but also the thermal stabilities of the sample, the sample jigs, and the mounting plate. This paper is focused on the thermal stability of the chromatic confocal probe since the thermal stabilities of the sample, the sample jigs, and the mounting plate change when the probe is employed for different applications.

2. Thermal Stability of the Chromatic Confocal Measurement Setup

2.1. Principle of the Femtosecond Laser Chromatic Confocal Probe

A schematic of the design of the overall chromatic confocal measurement setup, which is referred to as the first prototype measurement setup, is shown in Figure 1. The setup is composed of a mode-locked femtosecond laser chromatic confocal probe, which is referred to as the first prototype probe, a sample unit composed of the sample and the sample jigs, and the mounting plate on which the probe and the sample unit are placed. A photograph of the setup is shown in Figure 2. Figure 2a shows the
photograph of the overall first prototype measurement setup, and Figure 2b shows the sample unit. The probe and the sample unit are placed on the mounting plate made of stainless steel.

Figure 1. A schematic of the first prototype chromatic confocal measurement setup.

Figure 2. Photograph of the first prototype chromatic confocal measurement setup: (a) Photograph of the overall chromatic confocal measurement setup; (b) Photograph of the sample unit composed of a sample and sample jigs. (CL: Collimating lens, BS: Beam splitter, PBS: Polarized beam splitter, QWP: Quarter-wave plate, L1 and L2: Fiber coupling lenses).

Figure 3 shows the principle of the proposed femtosecond laser chromatic confocal probe [24,25]. In the probe, a mode-locked femtosecond laser source is employed as the light source. The wavelength of \( i \)th mode \( \lambda_i \) in a mode-locked femtosecond laser is well known to be expressed by the following equation [26–28]:

\[
\lambda_i = \frac{c}{\nu_{\text{rep}} + \nu_{\text{CEO}}}
\]  

where \( c \) is the speed of light, \( \nu_{\text{rep}} \) is the pulse repetition rate, and \( \nu_{\text{CEO}} \) is the carrier envelope offset frequency. The femtosecond laser beam from the laser source (MenloSystems Inc., Germany, C-Fiber-SYNC100) with an average output power of 30 mW was transmitted to the optical setup by a single-mode fiber. A pulse repetition rate of the femtosecond laser was set to be 100 MHz. A spectral
where the focal plane of L1, while the other (Detector2) is placed at the position with a defocus $d$ (≠ 0) from the focal plane of L2. The sub-beams are then transmitted to an optical spectrum analyzer through the single-mode fibers to obtain the optical spectra of the measurement beam $I_{\text{mea}}$ and the reference beam $I_{\text{ref}}$, and then the normalized axial response $I_n$ is analyzed.

$$f_{\lambda i} = \frac{1}{(n_{\lambda i} - 1)(1/R_1 - 1/R_2)}$$

where $R_1$ and $R_2$ represent the curvature radii of the chromatic objective lens [29], and $n_{\lambda i}$ is the refractive index of the lens material that can be expressed by the following equation:

$$n_{\lambda i} = \sqrt{1 + \frac{B_1 \lambda_i^2}{\lambda_i^2 - C_1} + \frac{B_2 \lambda_i^2}{\lambda_i^2 - C_2} + \frac{B_3 \lambda_i^2}{\lambda_i^2 - C_3}}$$

where $B_k$ and $C_k$ ($k = 1, 2, 3$) are the parameters inherent to the lens material [30]. The relationship between $\lambda_i$ and $f_{\lambda i}$ can therefore be uniquely identified by Equation (2). The laser beam reflected from the flat mirror surface passes the chromatic objective lens and the PBS again, and is reflected by the PBS. After that, the laser beam is split into two sub-beams (the measurement beam and the reference beam) by a beam splitter (BS). In the probe, a pair of identical single-mode fibers is employed as point detectors. The measurement beam is coupled into one of the single-mode fibers by using a fiber coupling lens (L1), while the reference beam is coupled into the other single-mode fiber by using another fiber coupling lens (L2). It should be noted that one of the fiber detectors (Detector1) is placed at the focal plane of L1, while the other (Detector2) is placed at the position with a defocus $d$ (≠ 0) from the focal plane of L2. The sub-beams are then transmitted to an optical spectrum analyzer through the single-mode fibers to obtain the optical spectra of the measurement beam $I_{\text{mea}}$ and the reference beam $I_{\text{ref}}$, and then the normalized axial response $I_n$ is analyzed.

**Figure 3.** Principle of the mode-locked femtosecond laser chromatic confocal probe (BS: Beam splitter, PBS: Polarized beam splitter, QWP: Quarter-wave plate, L1 and L2: Fiber coupling lenses).
In the proposed chromatic confocal probe, a fiber-based dual-detector is introduced to eliminate the influence of the non-smooth spectrum of the mode-locked laser source [20,24]. Based on the spectra $I_{\text{mea}}$ and $I_{\text{ref}}$ obtained by Detector1 and Detector2, respectively, a normalized axial response $I_n$ expressed by the following equation can be obtained:

$$I_n = \frac{I_{\text{mea}}}{I_{\text{ref}}}$$

(4)

Figure 4a shows an example of the spectra obtained by the pair of single-mode fibers. Each of the obtained spectra ($I_{\text{mea}}$ and $I_{\text{ref}}$) is the consequence of the convolution of the axial response of the confocal setup and the spectrum of the light source. It should be noted that the influences of the reflectance of the target surface as well as the transmittances of optical components in the setup also influence the obtained spectra. Since the femtosecond laser source has the non-uniform spectrum, the obtained spectra $I_{\text{mea}}$ and $I_{\text{ref}}$ also become non-uniform. This means that it is difficult to directly extract the peaks in the light spectra, which are required to obtain the axial position information of a measurement target surface under inspection. Meanwhile, by introducing the normalized axial response $I_n$ expressed by Equation (4), the influences of the non-uniformity in the spectrum of the light source as well as the surface reflectance can be canceled through the normalization process. Furthermore, by employing identical fiber coupling lenses and single-mode fibers for obtaining both $I_{\text{mea}}$ and $I_{\text{ref}}$, influences of the transmittances of these optical components can also be minimized through the normalization process. Figure 4b shows the normalized axial response $I_n$ obtained by $I_{\text{mea}}$ and $I_{\text{ref}}$ shown in Figure 4a. As can be seen in this figure, the valley in $I_{\text{ref}}$ is detected as the peak in the normalized axial response. It should be noted that the peak in the normalized axial response is sharper than those in $I_{\text{mea}}$ and $I_{\text{ref}}$. In the confocal system, the sharper peak in the axial response contributes to the realization of higher accuracy in identifying the focused wavelength $\lambda_{\text{focused}}$, and hence the higher resolution in measurement of the axial displacement.

Figure 5 shows the procedure of how to obtain the axial position information of the measurement target surface under inspection from the normalized axial response. Figure 5a shows the normalized axial response $I_n$. The wavelength $\lambda_{\text{focused}}$ at the peak in the normalized axial response, which is referred to as the focused wavelength, can be obtained by the following equation:

$$\lambda_{\text{focused}} = \frac{\sum (I_n(\lambda_i) \times \lambda_i)}{\sum I_n(\lambda_i)}$$

(5)

Figure 5b shows a schematic of the relationship between the focused wavelength $\lambda_{\text{focused}}$ and the Z position information of the measurement target surface. The Z displacement of the target sample surface can be calculated by the following equation:

$$\Delta Z = \frac{dZ}{d\lambda} \cdot \Delta \lambda_{\text{focused}}$$

(6)

where $dZ/d\lambda$ corresponds to the Z displacement detection sensitivity with respect to the change in the focused wavelength $\lambda_{\text{focused}}$. The sensitivity $dZ/d\lambda$ can be theoretically calculated, since the relationship between the focal length $f_{\lambda_i}$ of the chromatic objective lens and the corresponding light wavelength $\lambda_i$ can be calculated based on Equations (2) and (3). According to the specification of the chromatic objective lens employed in the first prototype confocal probe (the details of which can be found in Reference [24]), $f_{\lambda_i}$ sensitivity ($df/d\lambda$) is calculated to be 255 nm/nm. It should be noted that the positive direction of the Z displacement of the target sample surface is set as the direction the sample approaches the chromatic objective lens; namely, $df/d\lambda = (-dZ/d\lambda)$. The sensitivity $dZ/d\lambda$ is therefore calculated to be $-255$ nm/nm.
Experimental results have demonstrated that the first prototype confocal probe has an axial resolution of 30 nm [24]. Since the fiber-based dual-detector normalization method makes it possible to measure the axial displacement without the influence of the non-uniform spectrum of the light source, an axial displacement measurement range of 40 μm has been realized by fully utilizing a spectral range of 160 nm of the femtosecond laser [24]. The displacement measurement is also not influenced by the surface reflectance of the target sample, as well as the transmittance of optical components in the probe.

\[ \frac{dZ}{d\lambda} = \frac{-255 \text{ nm/μm}}{\lambda} \]

(b) : Z-λ sensitivity

Figure 5. Principle of a method to obtain the Z displacement and Z-λ sensitivity: (a) Focused wavelength extracted from the normalized axial response \( I_n \) and \( \lambda_{\text{focused}} \); (b) Z displacement calculated by using the Z-λ sensitivity.
On the other hand, due to the slow measurement throughput of the optical spectrum analyzer, it takes quite a long time (approximately 8 s) to take the spectra \( I_{\text{mea}} \) and \( I_{\text{ref}} \) at a position in a sample plane. Good thermal stability of the probe is thus required to apply the probe for long-term displacement measurement or surface profile measurement with multi-point scanning. For this purpose, it is important to identify the thermal stability of the developed probe in axial displacement measurement. It should be noted that the thermal stability of the overall chromatic confocal measurement setup is contributed by not only the thermal stability of the chromatic confocal probe itself but also the thermal stability of the sample, the sample jig, and the mounting plate (Figure 1). From the point of view of the developed femtosecond laser chromatic confocal probe, it is necessary to separate the thermal stability of the probe from those of the sample, the sample jig, and the mounting plate. Since it is difficult to directly measure the thermal stability of the probe, in the rest of this section, the thermal stability of the overall measurement setup shown in Figure 1 is measured first. Then an analytical work is carried out in the next section to characterize the thermal stability of the first prototype probe.

2.2. Experimental Verification of the Thermal Stability of the Overall Chromatic Confocal Measurement Setup

It is difficult to directly obtain the thermal stability of the overall measurement setup for axial displacement measurement \((dZ/dT)\). Meanwhile, the Z-\( \lambda \) sensitivity \((dZ/d\lambda)\) can be theoretically calculated as described above. Therefore, by obtaining the thermal stability of the detection of focused wavelength \((d\lambda/dT)\) in experiments, \(dZ/dT\) can be calculated from the following equation:

\[
\frac{dZ}{dT} = \frac{d\lambda}{dT} \frac{dZ}{d\lambda} \quad (7)
\]

To obtain the thermal stability of the detection of focused wavelength \((d\lambda/dT)\), experiments were carried out by using the setup shown in Figure 2. A flat mirror, which was employed as the target sample, was held stationary in the setup while a variation of the focused wavelength \(\lambda_{\text{focused}}\) was observed at each 100 s over a period of 5000 s. As can be seen in Figure 2b, a temperature sensor was placed in the optical setup to monitor the temperature deviation. Figure 6 shows the result of the thermal stability of the detection of focused wavelength \(\lambda_{\text{focused}}\) contributed by not only the thermal stability of the chromatic confocal probe itself but also the thermal stability of the sample unit and the mounting plate. It should be noted that experiments were carried out in a laboratory room whose temperature was controlled to be 20 °C ± 0.5 °C, while the temperature periodically deviated in a few hours. As can be seen in the figure, a clear correlation can be found between the variation of \(\lambda_{\text{focused}}\) and the change in temperature. Three repetitive experiments were carried out, and a mean value of \(d\lambda/dT\) was evaluated to be \(-20.4 \text{ nm/°C}\). Therefore, from Equation (7), the thermal stability of the overall measurement setup for axial displacement measurement \((dZ/dT)\) was evaluated as \(dZ/dT = (-20.4 \text{ nm/°C})(-255 \text{ nm/nm}) = 5.20 \mu\text{m/°C}\).

![Figure 6](image-url)  
Figure 6. The thermal stability of the focused wavelength \(\lambda_{\text{focused}}\) of the overall measurement setup evaluated in the experiment by the setup shown in Figure 2.
This result means that a temperature variation in the laboratory room ranging from 19.5 °C to 20.5 °C could result in a deviation of the detected axial displacement of ±2.60 µm in the overall chromatic confocal measurement setup. Regarding long-term displacement measurement or surface profile measurement where long-time scanning is required, the thermal stability of the developed chromatic confocal probe needs to be improved. A detailed investigation is therefore carried out in the following section to separate and characterize the thermal stability of the femtosecond laser chromatic confocal probe based on the measurement result of the overall measurement setup in Figure 6.

3. Characterization of the Thermal Stability of the Femtosecond Laser Chromatic Confocal Probe

The possible factors contributing to the thermal stability of the overall measurement setup are shown in Table 1. The contribution of each factor is analyzed for characterizing the thermal stability of the probe itself.

<table>
<thead>
<tr>
<th>Item</th>
<th>Factor</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe</td>
<td>Refractive index instability of the chromatic objective lens</td>
<td>( P_1 = (dZ/dT)_{P1} )</td>
</tr>
<tr>
<td></td>
<td>Refractive index instability of the surrounding air</td>
<td>( P_2 = (dZ/dT)_{P2} )</td>
</tr>
<tr>
<td></td>
<td>Thermal expansion of mechanical jigs</td>
<td>( P_3 = (dZ/dT)_{P3} )</td>
</tr>
<tr>
<td></td>
<td>Thermal expansion of optical path length</td>
<td>( P_4 = (dZ/dT)_{P4} )</td>
</tr>
<tr>
<td></td>
<td>Thermal stability of the probe</td>
<td>( \bar{P} = (dZ/dT)_{\text{probe}} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( = P_1 + P_2 + P_3 + P_4 )</td>
</tr>
<tr>
<td>Sample unit</td>
<td>Thermal expansion of the sample</td>
<td>( S_1 )</td>
</tr>
<tr>
<td></td>
<td>Thermal expansion of the sample jig</td>
<td>( S_2 )</td>
</tr>
<tr>
<td></td>
<td>Thermal stability of the sample unit</td>
<td>( S = (dZ/dT)_{\text{sample unit}} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( = S_1 + S_2 )</td>
</tr>
<tr>
<td>Mounting plate</td>
<td>Thermal expansion of the mounting plate (corresponding to the thermal stability of the mounting plate)</td>
<td>( M = (dZ/dT)_{\text{Mounting plate}} )</td>
</tr>
<tr>
<td></td>
<td>Thermal stability of the overall setup</td>
<td>( O = (dZ/dT)_{\text{Overall}} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( = P + S + M )</td>
</tr>
</tbody>
</table>

(a) Contribution of the refractive index instability of the chromatic objective lens \( (P_1) \)

The relationship between the refractive index of a lens placed in a vacuum and the temperature \( T_0 \) (reference temperature @20 °C) is described by the following equation \([31,32]\):

\[
\frac{dn_{\text{abs}}(\lambda_i, T)}{dT} = \frac{n^2(\lambda_i, T_0) - 1}{2n(\lambda_i, T_0)} \left( D_0 + 2D_1\Delta T + 3D_2\Delta T^2 + \frac{E_0 + 2E_1\Delta T}{\lambda_i^2 - \lambda_{TK}^2} \right)
\]  

(8)

where \( \Delta T = (T - T_0) \) is temperature deviation from a reference temperature \( T_0 \), and \( D_p \) \( (p = 0, 1, 2), E_q \) \( (q = 0, 1) \) and \( \lambda_{TK} \) are the parameters inherent to the lens material. The physical parameters associated with the employed chromatic objective lens in this paper are presented in Table 2 \([32]\). Based on Equation (8), refractive index instability is calculated to be \(-1.0629 \times 10^{-6} \text{°C}^{-1}\) at \( \lambda_i = 1560 \text{ nm} \); this value corresponds to thermal instability of the focused wavelength \( d\lambda/dT \) of 0.0594 nm/°C from Equation (3). Therefore, the contribution of the refractive index instability of the chromatic objective lens in the thermal stability of the probe is calculated as \( P_1 = (0.0594 \text{ nm/°C}) \cdot (-255 \text{ nm/°C}) = -15.1 \text{ nm/°C} \) from Equation (7).
Table 2. The physical parameters of N-SF11 employed in the theoretical calculations [32].

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>$D_0$</td>
<td>$-3.56 \times 10^{-6}$</td>
</tr>
<tr>
<td>$D_1$</td>
<td>$9.20 \times 10^{-9}$</td>
</tr>
<tr>
<td>$D_2$</td>
<td>$-2.10 \times 10^{-11}$</td>
</tr>
<tr>
<td>$E_0$</td>
<td>$9.65 \times 10^{-7}$</td>
</tr>
<tr>
<td>$E_1$</td>
<td>$1.44 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\lambda_{TK}$</td>
<td>$0.294$</td>
</tr>
</tbody>
</table>

(b) Contribution of the refractive index instability of the surrounding air ($P_2$)

When the air refractive index $n_{air}$ and the lens refractive index $n_{lens}$ are defined, Equation (2) can be rewritten as follows:

$$f_{\lambda_1} = \frac{1}{(n_{lens}/n_{air} - 1)(1/R_1 - 1/R_2)}$$

(9)

Differentiating $f_{\lambda_1}$ with respect to $n_{air}$ gives the following equation:

$$\frac{df}{dn_{air}} = \frac{1}{n_{lens}(n_{lens}/n_{air} - 1)} \left( \frac{n_{lens}}{n_{air}^2} \right)$$

$$= \frac{n_{lens}^2}{n_{air}(n_{lens} - n_{air})} \cdot f$$

(10)

Modifying the above equation gives the following equation:

$$\frac{df}{dT} = \frac{n_{lens}}{n_{air}(n_{lens} - n_{air})} \cdot f \cdot \frac{dn_{air}}{dT} = \frac{dZ}{dT}$$

(11)

Here, the air refractive indices of the lens ($n_{lens}$) and the air ($n_{air}$) at the reference temperature are 1.7432 (at $\lambda = 1560$ nm) and 1.00027, respectively. According to Ciddor’s theoretical formula [33], the refractive index instability of the air ($dn_{air}/dT$) is approximately $-1.0 \times 10^{-6}$°C. Therefore, from Equation (11), the contribution of the refractive index instability of the surrounding air in the thermal stability of the probe is calculated as $P_2 = -24.7$ nm°C at $\lambda = 1560$ nm.

(c) Contributions of the thermal expansion of mechanical jigs ($P_3$) and the mounting plate ($M$)

Figure 7 shows a detailed schematic of the chromatic confocal lens and the target sample in the measurement setup shown in Figure 2b. Now we consider the variation of the distance between the target sample and the chromatic objective lens in the setup. With the thermal expansion of components in the measurement setup such as the probe, the sample, the sample jig and the mounting plate, the distance between the chromatic objective lens and the sample can be changed. As the first step of the research, the thermal expansion of the sample and that of the sample jig are not considered for clarity in the following of this paper, since their contributions to the probe instability are expected to be relatively smaller than that of Jig-B, which is much longer than the other jigs in the probe. It should be noted that the thermal expansion of the sample and that of the sample jig will be taken into consideration for more accurate characterization of thermal stability in future work. In general, the linear thermal expansion of an object can be described by the following equation:

$$d\ell = \alpha \cdot \ell \cdot dT$$

(12)

where $d\ell$ is the change in the length of the object with the original length $\ell$, and $\alpha$ is the linear coefficient of thermal expansion of the object [34]. Here, since the object is expected to expand the same amount in both the directions from its center, $|dZ|$ can be treated to be equal to $|d\ell/2|$. From this equation, the contribution of the thermal expansion of a component in the measurement setup can be expressed by the following equation:
\[
\frac{dZ}{dT} = \pm \alpha A = \pm \alpha B \cdot \ell A \frac{\ell B}{2}
\]  

(13)

where the subscript A is the name of the component, and the subscript B is the kind of the component material. Here, the sign “±” in the equation is determined by the location of the object in the measurement setup. When the chromatic objective lens approaches the target sample due to the thermal expansion of the object, the sign is determined as “positive (+)”. Based on the above equation, the contributions of the thermal expansion of mechanical jigs in the probe (P3) and the mounting plate (M) are investigated.

Figure 7. A detailed schematic of the chromatic confocal lens and the target sample in the chromatic confocal measurement setup shown in Figure 2b.

At first, the contribution of the thermal expansion of mechanical jigs in the probe (P3) is investigated. The main contributor in the mechanical jigs is Jig-B, which connects the lens holder and Jig-A, since its length is the longest among the other jigs in the probe. It should be noted that the influences of other contributors such as Jig-A or lens holders are not considered at this stage, since the influence of Jig-B is dominant. It should also be noted that the influence of the displacement of the flat mirror in the X-direction due to the thermal expansion was expected to be relatively small compared with the main factor regarding a diameter of the focused beam (20 μm) and out-of-flatness of the flat mirror employed in the following experiment (λ/10@633 nm). When the temperature rises, the chromatic objective lens approaches the target sample due to the thermal expansion of Jig-B, which is made of aluminum having a linear thermal expansion coefficient of 23.1 × 10⁻⁶ °C⁻¹ [34] and its line length is designed to be 430 mm. From Equation (13), the contribution of the Jig-B in the thermal stability of the probe is evaluated as 

\[ P_3 = 4.96 \, \mu m/°C. \]

The contribution of the mounting plate M is also investigated. As opposed to the case of Jig-B, the chromatic objective lens moves away from the sample due to the thermal expansion of the mounting plate. The mounting plate is made of stainless steel having a linear thermal expansion coefficient of 14.7 × 10⁻⁶ °C⁻¹ [34], and its line length is designed to be 100 mm. From Equation (13), the contribution of the mounting plate is therefore calculated as 

\[ M = (dZ/dT)_{\text{Mounting plate}} = -0.735 \, \mu m/°C. \]

(d) Contribution of the thermal expansion of optical path length (P4)

Figure 8 shows a schematic of the optical setup in the chromatic confocal probe. Here, we define 

\[ dZ_{\lambda i} \]

as the axial distance between the focal position of the optical mode with the wavelength \( \lambda_{i+1} \) and that with the wavelength \( \lambda_i \). According to the geometric relationship in the optical setup, the defocus of the \( i \)-th optical mode at the fiber detector \( dZ_{\lambda i}' \) corresponding to \( dZ_{\lambda i} \) can be expressed by the following equation:

\[
\frac{dZ_{\lambda i}'}{2dZ_{\lambda i}(L - f_{\lambda i} - F) + f_{\lambda i}^2}
\]  

(14)
where \( L \) is the distance between the chromatic objective lens and the fiber coupling lens, and \( F \) is the distance between the fiber coupling lens and the fiber detector. It should be noted \( F \) corresponds to the focal length of the fiber coupling lens. In this paper, the sum of \( L \) and \( F \) is treated to be the optical path length. In the first prototype chromatic confocal measurement setup, \( L \) and \( F \) were designed to be 500 mm and 16.6 mm, respectively. As can be seen in the equation, \( dZ_{\lambda i}' \) is affected by \( L \) and \( F \), resulting in the change of the axial response \( I_n \); namely, the focused wavelength \( \lambda_{\text{focused}} \) is affected by the thermal expansion of the optical path length.

![Figure 8. Schematic of the optical setup in the chromatic confocal probe.](image)

However, a theoretical investigation of the contribution of the thermal expansion of optical path length \( (P_4) \) is not an easy task since the equation of the normalized axial response \( I_n \) [24] is quite complex. In this paper, experiments were therefore carried out to evaluate \( P_4 \) quantitatively. At first, the contribution of the distance \( F \) between the fiber coupling lens and the fiber detector in \( P_4 \) was investigated. The contribution of \( F \) in \( P_4 \) can be calculated from the following equation:

\[
\frac{dZ}{dT} = \frac{dF}{dT} \frac{d\lambda}{dz} \frac{dZ}{d\lambda} \quad (15)
\]

In the above equation, \( dF/dT \) and \( dZ/d\lambda \) can be estimated from theoretical calculations. In the first prototype measurement setup, the fiber coupling lens and the detector were placed on a jig made of aluminum having a linear thermal expansion coefficient of \( 23.1 \times 10^{-6} \) ˚C\(^{-1} \) [34]. The line length of the jig, which corresponded to \( F \), was designed to be 16.6 mm in the first prototype measurement setup. From Equation (12), the thermal expansion sensitivity of the jig \( df/dT \) was evaluated to be 0.383 μm/°C. In addition, \( dZ/d\lambda \) is already known as \( dZ/d\lambda = -255 \text{ nm/} \circ \text{C} \) from the theoretical investigation described in the previous section of this paper. Meanwhile, the term \( d\lambda/dF \) in Equation (15) still remains to be addressed for the evaluation of \( dZ/dT \).

To obtain \( d\lambda/dF \), experiments were carried out by intentionally changing \( F \) in the measurement setup. A flat mirror was employed as the target sample, and was held stationary in the setup. The experiments were carried out in such a way that the parameter \( \delta \) in Figure 3, which corresponded to the defocus of Detector2 from the focal plane of the fiber coupling lens, was changed from 0 μm to 300 μm in a step of 20 μm, while the focused wavelength at each step was being observed. In the experiments, the deviation of the parameter \( \delta \) \((\Delta \delta)\) corresponded to \(-dF\) in Equation (15). It should be noted that the positive direction of the parameter \( \delta \) was set to be the one from the fiber detector to the fiber coupling lens. Figure 9a shows the relationship between \( \delta \) and the corresponding normalized axial responses \( I_n \) obtained in the experiments, and Figure 9b shows the relationship between \( \delta \) and the focused wavelength \( \lambda_{\text{focused}} \) extracted from the normalized axial responses \( I_n \) shown in Figure 9a. From the experimental results, the sensitivity \( d\lambda/dF \) was evaluated to be 0.5686 nm/μm. From Equation (15), the contribution of \( F \) in \( P_4 \) was therefore evaluated as \( dZ/dT = (0.383 \mu \text{m/} \circ \text{C})(0.5686 \text{ nm/} \mu \text{m})(-255 \text{ nm/} \circ \text{C}) = -55.5 \text{ nm/} \circ \text{C} \).
The contribution of the distance \( L \) between the chromatic objective lens and the fiber coupling lens in \( P_4 \) is also investigated. \( L (=500 \text{ mm}) \) corresponds to the sum of the lengths of the mounting plate and Jig-A. To estimate the thermal expansion of \( L (\Delta L) \), a finite element model (FEM) shown in Figure 10 is employed in this paper. From the result of FEM analysis (by the Autodesk Nastran In-CAD), \( \Delta L \) is estimated to be approximately 10 \( \mu \text{m} \); this value is small compared with \( L (=500 \text{ mm}) \), and the influence of \( \Delta L \) is negligibly small. From these results, it can be concluded that the contribution of \( F \) is much larger than that of \( L \) in the contribution of the thermal expansion of optical path length \( P_4 \). As a result, \( P_4 \) was evaluated to be \(-55.5 \text{ nm/°C}\). It should be noted that the uncertainty of \( L \) could increase the measurement uncertainty of the femtosecond laser chromatic confocal probe. Therefore, the optical path length \( L \) is expected to be reduced for the stabilization of the femtosecond chromatic confocal probe.

![Figure 9](image1.png)

**Figure 9.** Relationship between the defocus \( d \) and the focused wavelength \( \lambda_{\text{focused}} \): (a) The relationship between \( d \) and the obtained normalized axial responses \( I_0 \); (b) The relationship between \( d \) and the focused wavelength \( \lambda_{\text{focused}} \) extracted from the normalized axial responses shown in Figure 9a.

Table 3 summarizes the contribution of each factor on the overall thermal stability of the setup. In summary, the thermal stability of the overall measurement setup \((dZ/dT)_{\text{Overall}}\) is evaluated to be 4.13 \( \mu \text{m/°C} \) from the theoretical investigation. A difference of approximately 1 \( \mu \text{m/°C} \) can be found between the thermal stability estimated in theory (4.13 \( \mu \text{m/°C} \)) and that obtained in the experiments (5.20 \( \mu \text{m/°C} \)) described in the previous section of this paper; the difference is considered to be the sum of the small contributions from the other factors not considered in the theoretical calculations. From this result, it can be concluded that the reductions of the line lengths of Jigs-A and -B, and the
mounting plate as well as the employment of low thermal expansion materials for the Jig-B and jigs in the overall setup, are expected to stabilize the femtosecond laser chromatic confocal probe.

Table 3. Summary of the contribution of each factor on the overall thermal stability of the setup.

<table>
<thead>
<tr>
<th>Item</th>
<th>Factor</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe</td>
<td>Refractive index instability of the chromatic objective lens</td>
<td>( P_1 = -0.0151 , \mu m/°C )</td>
</tr>
<tr>
<td></td>
<td>Refractive index instability of the surrounding air</td>
<td>( P_2 = -0.0247 , \mu m/°C )</td>
</tr>
<tr>
<td></td>
<td>Thermal expansion of mechanical jigs</td>
<td>( P_3 = 4.96 , \mu m/°C )</td>
</tr>
<tr>
<td></td>
<td>Thermal expansion of optical path length</td>
<td>( P_4 = -0.0555 , \mu m/°C )</td>
</tr>
<tr>
<td></td>
<td>Thermal stability of the probe</td>
<td>( P = P_1 + P_2 + P_3 + P_4 = 4.86 , \mu m/°C )</td>
</tr>
<tr>
<td>(Sample unit)</td>
<td>(Thermal expansion of a sample)</td>
<td>( (S_1) )</td>
</tr>
<tr>
<td></td>
<td>(Thermal expansion of sample jig)</td>
<td>( (S_2) )</td>
</tr>
<tr>
<td></td>
<td>(Thermal stability of the sample unit)</td>
<td>( (S = S_1 + S_2) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not considered</td>
</tr>
<tr>
<td>Mounting plate</td>
<td>Thermal expansion of the mounting plate, corresponding to the</td>
<td>( M = -0.735 , \mu m/°C )</td>
</tr>
<tr>
<td></td>
<td>thermal stability of the mounting plate</td>
<td></td>
</tr>
<tr>
<td>Thermal stability of the overall setup</td>
<td>( O = P + S + M )</td>
<td>( = 4.13 , \mu m/°C )</td>
</tr>
</tbody>
</table>

4. Improvement of the Thermal Stability of the Femtosecond Laser Chromatic Confocal Probe

Aiming to improve the thermal stability of the chromatic confocal probe, a second prototype measurement setup was newly designed and developed. It should be noted that the thermal stability of the overall chromatic confocal measurement setup is contributed by not only the thermal stability of the chromatic confocal probe itself but also the thermal stabilities of the sample, the sample jig, and the mounting plate. This paper is focused on the improvement of the thermal stability of the chromatic confocal probe itself, since the thermal stabilities of the sample, the sample jigs, and the mounting plate change when the probe is employed for different applications. To improve the thermal stability of the femtosecond laser chromatic confocal probe, attentions were paid to choose a material having a low thermal expansion coefficient for the major mechanical component (Jig-B) in the chromatic confocal probe, while the optical path length was designed to be as short as possible. Figure 11 compares the previous first prototype measurement setup and the newly developed second prototype measurement setup. As can be seen in the figure, the size of the second prototype measurement setup is reduced to be 1/6 of that of the first prototype measurement setup. For a fair comparison, optical components identical to those employed in the first prototype measurement setup were employed in the second prototype measurement setup, while the material of Jig-B was switched from aluminum to Super Invar having a far lower thermal expansion coefficient compared with aluminum [35,36]. All the optical components and jigs were mounted on an aluminum optical breadboard.

At first, the improvement of the thermal stability of the second prototype measurement setup was verified in theoretical calculations. By the modifications described above, the optical path length in the second prototype measurement setup was reduced to be approximately 1/6 of that of the previous first prototype measurement setup. The thermal stability of the newly designed second prototype measurement setup is estimated in the same manner as the previous first prototype measurement setup described in the previous section of this paper. Table 4 summarizes the contribution of each factor in the thermal stability of the probe in the second prototype measurement setup. The thermal stability of the chromatic confocal probe in the second prototype measurement setup \( (0.0197 \, \mu m/°C) \) is far better than that in the first prototype measurement setup \( (4.86 \, \mu m/°C) \). This result implies that the sub-micrometric stability of the femtosecond laser chromatic confocal probe can be achieved by the second prototype measurement setup.
To evaluate the thermal instability of the probe, the contribution of the mounting plate is estimated in the theoretical calculation (0.0197 μm/°C in the first prototype measurement setup). The mounting plate is made of aluminum having a linear thermal expansion coefficient of 23.1 μm/°C. It should be noted that this result contains the contribution of the thermal expansion of the mounting plate. To evaluate the thermal instability of the probe, the contribution of the thermal expansion of the mounting plate must be noted.

Experiments were then carried out to verify the improvement of the thermal stability of the second prototype measurement setup. Three repetitive experiments were carried out. Figure 12 shows one of the experimental results. A mean value of \( dZ/dT \) was evaluated to be 7.9 nm/°C. Therefore, from Equation (7), the thermal stability of the overall second prototype measurement setup for axial displacement measurement \( (dZ/dT)_{\text{Overall}} \) was evaluated as \( (dZ/dT)_{\text{Overall}} = (7.9 \text{ nm}/°C)(−255 \text{ nm/nm}) = −2.01 \mu\text{m}/°C \). It should be noted that this result contains the contribution of the thermal expansion of the mounting plate. To evaluate the thermal instability of the probe, the contribution of the mounting plate is estimated in theory. Figure 13 shows the schematic of the chromatic confocal lens and the target sample in the second prototype measurement setup. The mounting plate is made of aluminum having a linear thermal expansion coefficient of 23.1 × 10\(^{-6}\) °C\(^{-1}\) [34]. Regarding a length of the mounting plate (175 mm), from Equation (12), the contribution of the mounting plate is calculated as \( (dZ/dT)_{\text{Mounting plate}} = (23.1 \times 10^{-6} \text{ °C}^{-1})(175/2 \text{ mm}) = −2.02 \mu\text{m}/°C \). Considering the result of the above theoretical calculation, the thermal stability of the second prototype chromatic confocal probe is evaluated as follows:

\[
(dZ/dT)_{\text{Probe}} \approx (dZ/dT)_{\text{Overall}} - (dZ/dT)_{\text{Mounting plate}} = (-2.01 \mu\text{m}/°C) - (-2.02 \mu\text{m}/°C) = 0.01 \mu\text{m}/°C
\]  

As can be seen in the equation, the thermal stability of the second prototype chromatic confocal probe (0.01 μm/°C) was successfully improved compared with that of the first prototype chromatic confocal probe (4.86 μm/°C). The result obtained through the experiments was also close to that predicted in the theoretical calculation (0.0197 μm/°C), which also demonstrated the improvement of the thermal stability of the newly developed second prototype chromatic confocal probe.
The results of theoretical calculations and experiments have demonstrated that the femtosecond probe with a mode-locked femtosecond laser source. At first, the thermal characteristics of the previous first prototype femtosecond laser chromatic confocal measurement setup have been verified through experiments, and the thermal stability has been evaluated to be 5.20 μm/°C.

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Figure 12. The thermal stability of focused wavelengthλfocused of the overall second prototype measurement setup shown in Figure 11b.

Figure 13. A schematic of the chromatic confocal lens and the target sample in the second prototype chromatic confocal measurement setup shown in Figure 11b.

5. Conclusions

In this paper, efforts have been made to improve the thermal stability of the chromatic confocal probe with a mode-locked femtosecond laser source. At first, the thermal characteristics of the previous first prototype femtosecond laser chromatic confocal measurement setup have been verified through experiments, and the thermal stability has been evaluated to be 5.20 μm/°C. Theoretical investigations on the possible reasons for the thermal instability of the probe, such as the thermal instability of the refractive index of the confocal lens and the thermal expansion of mechanical jigs of the probe, have then been carried out. Through the quantitative analysis of the contribution of each possible reason, the mechanical jig, on which the lens holder is mounted, and the mounting plate have been found to be major contributors in the instability of the measurement setup. Regarding the results of theoretical investigations, the second prototype measurement setup has newly been designed and developed. In the second prototype measurement setup, attentions have been paid to minimize the optical path length of the laser beam in the setup, while Super Invar has been employed as the material for the mechanical jig for the improvement of the thermal stability of the chromatic confocal probe. The results of theoretical calculations and experiments have demonstrated that the femtosecond laser chromatic confocal probe in the second prototype measurement setup has achieved thermal stability of 0.01 μm/°C, which is far better than that in the previous first prototype measurement setup (4.86 μm/°C).

It should be noted that attention has been paid in this paper to improving the thermal stability of the chromatic confocal probe with a mode-locked femtosecond laser source. Application of the developed optical setup for surface profile measurement is the next step of the research, and will be carried out in future work.
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References


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