1. Introduction

Rise in working temperature, high power and high power density of electronic components are advancing mainly in the automotive electronic circuits in recent years, so the importance of thermal management of electronic components are increasing. The infrared thermograph has become affordable in price and easier to use so that anyone can manipulate it like visible light cameras. Therefore, electronic device designers are able to use the infrared thermograph frequently for the temperature measurement at the designing stage of the element of circuits and printed circuit boards.

The following basic point is well known. That is, when measuring the accurate temperature using the infrared thermograph, it is necessary to adjust the emissivity beforehand. However, when it comes to measuring the temperature of a microscopic area, the size of the target required to catch the peak temperature in the area is not well known. In most cases, this relationship is not disclosed by the infrared thermograph manufacturers. In the case of the standard equipped lens of the infrared thermograph, the disclosed information is the view angle which corresponds to 1 pixel of the light receiving element. On the other hand, when the high magnification percentage fixed focus lens is used to measure the temperature of a microscopic target such as the electronic component, the information opened is the relationship between the size of the photographic subject and 1 pixel of the light receiving element.

In this study, a method has been proposed, by which electronic device designers can estimate the spatial peak detection capability of a thermograph only by using equipment that are readily-accessible.
temperature region with 100 μm square can be measured if the region is observed with a 100 μm lens. However, as exemplified in Fig. 2, the peak temperature cannot be measured. That is, the peak temperature can be measured when the region to be measured is several times larger than 100 μm square. This can be regarded as the influence of the modulation transfer function (MTF) of the whole measurement system of the infrared thermograph including the area effect of the lens, and concrete cases are given later. The MTF is an index showing the spatial resolution of the images, and usually has the characteristic of a spatial low-pass filter as shown in Fig. 3. The amplitude of temperature on the thermal image decreases as the spatial frequency becomes higher. When it is compared in case of stripe of bright and dark, it means if the distance between bright and dark parts is shorter, the difference of brightness level between bright and dark parts becomes smaller. When considering the influence to the temperature distribution measurement, if many high and low temperature parts are repeated in a short distance, the high temperature parts are apt to cause errors in the low temperature side, and vice versa.

In this study, by supposing the MTF of the infrared thermograph as the Gaussian filter, a simple method for estimating the minimum area, which can capture the peak temperature, has been proposed by using elementary image processing and inexpensive equipment.

2. Magnification of Lens and Peak Detection Capability

2.1 Measuring object

First of all, the structure of the surface mount device (SMD) resistor to be measured of its temperature distribution is explained using Fig. 4. The SMD resistors are taken up here as an example since they are representative small electronic components. The base material of the SMD resistor is made of alumina ceramic which has good thermal conductivity. Terminals are formed on both ends of the base material to connect electrically and mechanically to the copper foil pattern on the printed board. The common connecting means is soldering. The resistive element is formed in membrane between the electrodes, and the linear trace of evaporation made by laser can be seen in the center of the resistive element. The trace is implemented in the manufacturing process to adjust to the desired resistance value, and is called the trimming line.

When potential difference is given between both terminals and electric power is supplied to the resistive element, high power density is formed locally at the tip of the trimming line. This makes the tip temperature higher than the other parts, and the locally higher temperature part is called the hotspot of a resistor. Usually, this hotspot cannot be visually observed. This is because there is coating layer on top of the resistive element for protection. The hotspot being observed through the coating is called the surface hotspot. In the design of electronic devices, from the standpoint of the thermal management on SMD resistors, not only the terminal part temperature measurement is important, but also the peak temperature measurement of the surface hotspot is important for safety.[1]

![Fig. 2 Example of peak temperature measurement by 100 μm lens.](image)

![Fig. 3 Modulation transfer function.](image)

![Fig. 4 Structure of SMD resistor.](image)
2.2 Differences in measured hotspot temperature by lens magnification

Figure 5 shows the results of the temperature distribution measured by the infrared thermograph equipped with various magnification lenses. Here, the power 0.25 W was supplied to a surface mount fixed resistor of 1.6 mm in length, 0.8 mm in width (commonly known as 1608 mm size resistor) which was mounted on a printed board.

The temperature distribution was measured along the dotted line in the longitudinal direction of the resistor surface as shown in the bottom of the figure. This path was selected so as to include the hotspot. As a matter of course, the peak temperature is observed on the hotspot, but it is obvious that the peak temperature is measured low when the lens with low magnification, or the lens with large \(X\) [\(\mu m\)] value are used. On the other hand, no significant difference is found when measuring the terminal part temperature no matter which lens is used. The fact that the terminal part temperature shows almost no difference becomes important in the application part mentioned later.

It should be noted that the peak detection capability of the 100 \(\mu m\) lens is significantly inferior to the 25 \(\mu m\) lens. That is, the peak temperature measured by the 100 \(\mu m\) lens is not equivalent to the average temperature measured at the 4 points close to the peak by the 25 \(\mu m\) lens. It is the same with the comparison of the 100 \(\mu m\) lens and the 200 \(\mu m\) lens. As mentioned above, the peak temperature of the measured object which has high temperature only in the 100 \(\mu m\) square cannot be measured with a 100 \(\mu m\) lens even when the pixel is set in the center and covered the whole pixel.

As a result of simulation, the surface hotspot of the resistor in the figure is estimated around 100 \(\mu m\) in diameter. When this temperature distribution is measured with the infrared thermograph, it has been clarified that the 25 \(\mu m\) lens would be the lower limit of the magnification power to capture the peak temperature.[2]

3. MTF Estimation

3.1 Conventional method and its problems

The traditional MTF measurement is shown as the conceptual diagram in Fig. 6. A shielding board with a slit is set in front of the quasi black surface whose temperature is kept constant and the temperature distribution including the slit is measured. This method is summarized as recommendations in the references.[3]

Methods like this may be required to calculate the exact MTF. However, most of the lenses with high magnification power are fixed-focus macro lenses. For example, the 25 \(\mu m\) lens used in this experiment can be focused only when the distance between the photographic subject and the lens is set around 10 mm. Therefore, it is considered that making up a measurement system like shown in the figure would be extremely difficult.

The biggest problem is that the measurement method mentioned above is not a method which electronic device designers having no other special equipment can easily perform.

3.2 Evaluation based on local emissivity changes of uniformly heated plane surface

The method proposed in this study is devised for electronic device designers, so the method uses only the equipment that the device designers can use freely. The measurement system is shown in Fig. 7. In general, it is difficult to realize a clear boundary of temperature difference in a microscopic region. By using the infrared thermograph, however, it is possible to realize the clear boundary in a stepwise pattern under the same temperature without making up a boundary of actual temperature difference.

In this study, a method for estimating the spatial resolu-
tion of the measurement system has been proposed. In the method, the temperature distribution of the boundary with different emissivity was measured by using the infrared thermograph whose MTF needs to be estimated. And from the slope of the transition part (from the highly measured part due to the high emissivity to the lowly measured part due to low emissivity), the spatial resolution was evaluated. In other words, from the quasi step response of temperature produced by the differences in emissivity against the infrared thermograph, the temperature peak detection capability of microscopic region is determined by image processing. Here, the cutoff spatial frequency $f_c$ is estimated by using MTF as a spatial low-pass filter. The most commonly available jig board in Fig. 7 is the glass epoxy printed wiring board with no components on it, or a part of the so-called bare board. The value of the temperature itself measured by the infrared thermograph does not matter in the step response measurement. Therefore, it is not necessary to know the emissivity of the high emissivity part (solder resist part) and the low emissivity part (such as land part which solder leveling is applied) on the printed circuit board. It would be enough that the difference in emissivity of each region is large. However, the boundary separating each region needs to be a clear and straight line.

3.3 Specific procedure

In the first step, suppose that the MTF of the infrared thermograph is a Gaussian filter as shown in Fig. 8, and prepare a step response corresponding to various cutoff spatial frequencies. The vertical axis which corresponds to the temperature is normalized to 0 at low temperature and to 1 at high temperature. The Gaussian filter is used here to approximate the MTF since it is commonly used in signal processing of the image. There is no practical issue in determining the peak detection capability as long as it is recognized that some errors are to occur. In this study, the errors have been confirmed by using the special jig board. Usually the unit of the cutoff spatial frequency $f_c$ is cycle/mm, but in this study, for the purpose of facilitating the comparison with 1 pixel size, it is expressed in the cutoff spatial frequency half wavelength $L_{ch}$ [$\mu$m]. The relation between them is given by $L_{ch} = 1,000/(2f_c)$. For example, when the cutoff spatial frequency $f_c$ is 5 cycles/mm, then it is called $L_{ch} = 100$ $\mu$m.

In the second step, using the measurement system shown in Fig. 7, set the jig board on the hotplate and heat it up to 50°C above the room temperature. Then, measure the boundary temperature between the solder resist part which is the insulating part and has high emissivity (around 0.85 to 0.9) and the pad part which is metallic and has low emissivity (below 0.5 even when oxidized) with the infrared thermograph, and further obtain the normalized temperature distribution like shown in Fig. 9.

Finally, check up the theoretical value obtained in the first step and the measured value obtained in the second step. Then, define the theoretical value, which is the cutoff spatial frequency half wavelength and is closest to the actual measured value, as the index of MTF of the tested...
infrared thermograph.

In Fig. 10, examples of the cutoff spatial frequency half wavelength \( L_{ch} \) obtained for each lens are shown. The calculated value depicted by the solid line matches well with the measured value, respectively. Here, the 25 \( \mu \)m, 100 \( \mu \)m and 200 \( \mu \)m lenses in this example are those used to measure the temperature distribution of the resistor shown in Fig. 4.

The \( L_{ch} \) and the image of pixel size are shown in Fig. 11. As seen from Fig. 10, the cutoff spatial frequency half wavelength \( L_{ch} \) of the \( X [\mu m] \) lens is 3\( X [\mu m] \), and you can see that it is surprisingly long compared with the size of 1 pixel.

### 3.4 Confirmation of temperature peak detection capability of microscopic region

When the target cutoff spatial frequency half wavelength \( L_{ch} \) of measurement system is obtained, then according to the procedure shown in Fig. 12, the accuracy of the peak of the high temperature part of the arbitrary area can be confirmed by using the image processing. Here, an extreme case is used as an example in the figure. The inside part of the 100 \( \mu \)m square is 100°C and the other part is 0°C.

First, convert the original temperature distribution of the plane into the spatial frequency domain image by 2-Dimensional Discrete Fourier Transform (2DDFT). Next, apply the Gaussian filter with the cutoff spatial frequency \( f_c \) measured by the abovementioned procedure, and then perform the inverse transform to spatial temperature distribution again. If the reversed peak value of the temperature distribution is the same as the precipitous temperature distribution peak value (100°C) before conversion, then it is confirmed that this measurement system is able to catch the peak temperature of a small area, where only the inside part of 100 \( \mu \)m square is high temperature.

Figure 13 shows the result obtained by operating a Gaussian filter with a cutoff spatial frequency half wavelength \( L_{ch} = 75 \mu m \) to the original plane kept at 100°C, which was supposed in Fig. 12, by changing the size of the high temperature part of 100°C as 100 \( \mu \)m square, 150 \( \mu \)m square, and 200 \( \mu \)m square. It can be seen that, in order to catch the peak temperature by using the lens of \( L_{ch} = 75 \mu m \), the high temperature part needs to be larger than 150
μm square. This is two times larger than the $L_{ch}$.

Taken together with the results of the preceding section, the cutoff spatial frequency half wavelength $L_{ch}$ is $3X$ [$\mu m$], so the high temperature part must be larger than $6X$ [$\mu m$] square to catch the peak with a $X$ [$\mu m$] lens.

Though related to the verification in the next section, the reason the peak temperature of 100 $\mu m$ square sized hotspot is considered to be measured accurately with a 25 $\mu m$ lens is that the temperature of the surrounding part rises up to the hotspot temperature with a gentle slope.

If the temperature gradient up to the peak is gentle, the peak can be caught even with a comparatively low magnification lens. The details are omitted here, but in the procedures of Fig. 12, it can be confirmed that when the original temperature distribution is supposed as a slope to reach the peak and not a stepwise pattern, then the peak can be measured with a lower cutoff spatial frequency lens (or a lens with lower magnification).

### 3.5 Verification by temperature distribution of a resistor

Figure 14 is a comparison of calculated values, in which the Gaussian filter with cutoff spatial frequency half wavelength $L_{ch} = 300 \mu m$ (equivalent to 100 $\mu m$ lens) and $L_{ch} = 600 \mu m$ (equivalent to 200 $\mu m$ lens) were operated according to the procedures explained in Fig. 12. There, the temperature distribution of the resistor shown in Fig. 4 and the temperature distribution on the plane surface measured with a 25 $\mu m$ lens were supposed to be the true values. It can be seen that the calculated values almost agree with the measured ones.

Here, the image processing method by the Gaussian filter used in the verification of Fig. 12 has a broad range of applications. For example, the method can be introduced in the studies on extraction of the terminal part temperature from the temperature distribution image of SMD resistors. This application is necessary for the thermal management of SMD resistors.[4]

### 3.6 Verification by using special jig

Figure 15 shows an overview of a jig pattern. The pattern was developed for measuring the infrared thermograph peak detection capability more directly. It is used in place of a jig pattern shown in Fig. 7 by heating it on a hot plate. The base material is made of 0.7 mm thick alumina ceramic with higher thermal conductivity of $30 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ than the glass epoxy board. The high-emissivity part is alumina ceramic base material itself, and the low-emissivity part is platinum thin film with a thickness of 200 nm. The platinum thin film is formed on alumina ceramics by sputtering.

The present jig consists of high and low emissivity parts, so there is no difference from a bare board. The largest difference is that this board has micro squares with different sized high emissivity part A, B, C inside the low emissivity part, and has micro squares with different sized high emissivity part A', B', C' (same size with A, B, C) inside the low emissivity part. Heat the jig pattern on a hot plate, and measure the line profile of temperature along a-a', b-b', c-c' including the micro square with the infrared thermograph which you need to measure the peak detection capability. A schematic diagram of the measured line profile is shown.
in Fig. 16. In the measurement using this jig pattern, the slope of the boundary of the high emissivity part and low-emissivity part at the center of the line profile is not used.

Directions for use are as follows: The temperature observed in the high-emissivity part of large area is set as the high-temperature limit, and if the high emissivity micro shape formed inside the low emissivity area reaches the high-temperature limit, then it is confirmed that the infrared thermograph can detect the peak temperature of the size of the micro shape. On the other hand, if it does not reach the high-temperature limit, then it means that the peak temperature of the high temperature part with the size of the micro shape cannot be detected.

Conversely, the temperature observed in the low-emissivity part of large area is set as the low-temperature limit, and if the high emissivity micro shape formed inside the low emissivity area reaches the low-temperature limit, then it is confirmed that the infrared thermograph can detect the dip temperature of the size of the micro shape. On the other hand, if it does not reach the low-temperature limit, then it means that the dip temperature of the low temperature part with the size of the micro shape cannot be detected.

The reason for forming a pattern with a negative-positive relationship on the same board is that there could be a case in which the peak detection capability and the dip detection capability of the infrared thermograph do not necessarily match.

From the example of Fig. 16, in the case of the micro shape along the line a-a’, the line profile does not reach the high temperature limit nor the low temperature limit, so this means that the peak and the dip cannot be detected. In the same way, the peak can be detected but the dip cannot in the case of the micro shape along the line b-b’, and further, both the peak and the dip can be detected in the case of the micro shape along the line c-c’.

Figures 17 and 18 show the results of the detection capability measurement of the 25 μm and 100 μm lenses using this jig pattern.

From the line profiles obtained by using this special jig, unlike the prospectus, the temperature peak and dip of the micro shape marginally do not reach the high temperature limit and low temperature limit, respectively. Investigation of the cause is the future subject. As an alternative, determination of whether or not the peak and dip can be detected was done by comparing it with the ultimate temperature of the nearby larger micro shape. Using the judgement method of peak detection capability in Fig. 17 as an example, the ultimate temperature of 150 μm is the same as the larger micro shapes. It is clearly decreased for the smaller sizes. Therefore, 150 μm is deemed to be the peak detection limit.

According to such criteria, the minimum peak that a 25
\( \mu m \) lens can detect resulted in 150 \( \mu m \), and in 600 \( \mu m \) for a 100 \( \mu m \) lens. If the magnification power of the lens is \( X [\mu m] \), then the measured value of the peak detection capability is 6\( X [\mu m] \). Compared with the results shown in Fig. 13, it can be seen that the evaluation method of the peak detection capability proposed in this study using the approximation with the Gaussian filter and the image processing of the MTF is almost adequate.

4. Conclusions

A simple evaluation method for grasping the peak detection capability in small area of the infrared thermograph has been studied theoretically and experimentally, and its validity has been shown. From calculated and measured results, the following findings have been obtained.

(1) In order to detect the peak temperature of the square high temperature region by using the infrared thermograph with the lens magnification power \( X [\mu m] \), the area size must be larger than 6\( X [\mu m] \) square.

(2) It has been clarified that the peak and dip detection capabilities of the infrared thermograph can be easily evaluated by using the newly developed jig pattern for measuring the peak detection capability shown in Fig. 15.

(3) From the measured results obtained by applying the newly developed jig pattern, it has been proved that the Gaussian filter approximation of the MTF based on the step response measurement shown in Fig. 7 to Fig. 10 is valid.

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