



Article

Nanotexturing onto Laser-Microtextured Surface via Nickel Wet-Plating for IR-Emissivity Control

Tatsuhiko Aizawa ^{1,*} , Hiroki Nakata ² and Takeshi Nasu ²

¹ Surface Engineering Design Laboratory, Shibaura Institute of Technology, Tokyo 144-0056, Japan

² Ebinax, Co., Ltd., Tokyo 144-0033, Japan; nakata-h@ebinax.com (H.N.); nasu-t@ebinax.com (T.N.)

* Correspondence: taizawa@sic.shibaura-it.ac.jp; Tel.: +81-2-6424-8615

Abstract

Short-pulse laser machining was employed to transform the flat copper sheet into a micro-textured specimen. This specimen was further nanotextured using the nickel wet-plating to build up the IR (InfraRed)-emission metallic device with fractal-like surface. Four-unit cells were designed and fabricated as a micro-/nanotextured specimen by varying the microtextured unit cell structure. The IR-emissivity of these four specimens was measured using the thermographic microscopy with FT-IR (Fourier Transform InfraRed). The bare copper and nickel-nanotextured copper specimens were utilized as a reference. The micro-/nanotextured copper specimen had higher IR-emissivity than 0.8 in the wide wavelength range from 2 μm to 14 μm .

Keywords: picosecond laser microtexturing; nickel wet plating; nanotexturing; surface conditions; wettability; infrared emissivity

1. Introduction

Digital archiving, AI (Artificial Intelligence)-based informatics and high-speed data transformation stand on the huge usage of electric powers [1]. At each terminal, at every relay station and at all data centers, most of electric power wastes are dissipated as a heat source to increase the temperature at each CPU, connector and device [2]. Heat transfer from these heat sources via radiation to circumstances, heat convection with forced coolant flow, or boiling heat transfer with the use of two-phase flow are indispensable to preserve the device temperature below the criticality [3]. A heatsink was equipped to these devices for thermal spreading to coolants via convection heat transfer [4]; effective interface area must be increased to transfer the heat waste to cooling media. Surface microtexturing provides a way to broaden this interfacial area per a single device and to make full use of interfacial material system between heat sink and cooling media [5].

Lots of studies have been reported on the effect of surface microtextures on the IR (InfraRed) emissivity. In particular, semi-regular or regular alignments of nickel acicular unit cells onto the copper sheets induced much higher IR-emissivity than copper sheets with smooth surfaces [6]. To be noticed, the maximum intensity of IR-emissivity is around 0.4 to 0.5 for semi-regular or regular microtextures [7,8]; it reached 0.95 or more using the nanostructured photonics and the metamaterials [9,10]. Toward the efficient heat radiation heat transfer, a new device is needed to attain relatively high IR-emissivity in the wider IR-wavelength range irrespective of the device surface area.

In the present paper, a two-step procedure is developed to fabricate the micro-/nanotextured metallic sheet for IR-emission. At first, the tailored microtextures are formed



Academic Editor: Mohammad Rezayat

Received: 15 August 2025

Revised: 21 February 2026

Accepted: 10 March 2026

Published: 11 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

into a substrate A-material via the ultrashort pulse laser micromachining as depicted in Figure 1a. The wet-plating process is utilized to build up the B-material nanotextures onto this microtextured substrate, as shown in Figure 1b.

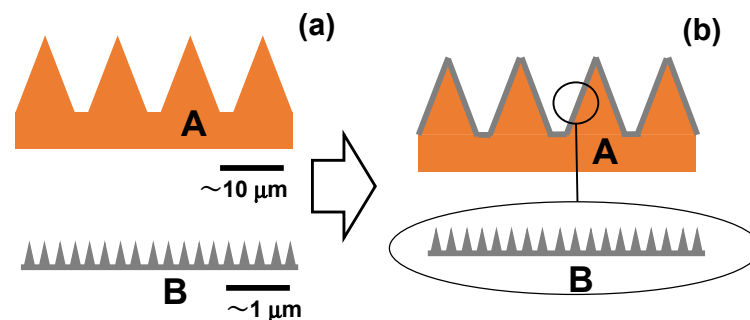


Figure 1. Synthesized surface structure by superposing the nanotextures on the microtextures. (a) Microtexturing onto the A-materials, (b) superposition of B-material nanotextures onto A-materials.

Four specimens are prepared by this two-step procedure to investigate the effect of micro-/nanotextured unit cell geometry on the IR-emissivity. The IR-emissivity for these specimens is also measured and compared among the microtextured and micro-/nanotextured surfaces with reference to the bare smooth copper and nickel-nanotextured copper sheets. The unit cell geometry of microtextures and nanotextures is analyzed by microstructural analyses.

2. Materials and Methods

A picosecond laser machining system was employed to build up the microtextures onto the bare smooth copper sheet. This specimen was further treated by the wet-plating to have nanotextured nickel layer after cleansing the laser-treated sheet surface. Four specimens with different microtextures from each other were prepared to investigate the effect of unit cell geometry on the measured IR-emissivity.

2.1. Micro-/Nanotexturing Design

A new metallic sheet device in Figure 1 was designed after various studies in the literature [11]. As depicted in Figure 1a, the unit cell depth for microtexturing was designed to be from 10 to 20 μm . The continuous resonance theory [12] suggested that the contour profile of unit cell worked as a continuous resonator up to the wavelength limit bound by the unit cell depth. In the following, this depth as well as the pitch among the neighboring unit cells are controlled to investigate their effect on the IR-emission with and without nanotextures.

2.2. Picosecond Laser Machining

The oxygen-free copper sheet (Mitsubishi Metals, Co., Ltd., Tokyo, Japan) was prepared and polished. Its purity was 99.99%. Its size was 50 mm $\times$ 50 mm $\times$ 0.5 mm. Its surface was microtextured by picosecond laser micromachining (AMADA, Co., Ltd.; Tokyo, Japan), as illustrated in Figure 2a. The beam spot size was constant by 10 μm using the biharmonic wave with its wavelength of 532 nm. The average power was 30 W. The pulse width was 8 ps, the pulse repetition rate was 200 kHz, and the fluence was 0.3 J/cm². The microtexture profile was determined to be adaptive to the wavelength range from near-IR to far-IR. In the CAM (Computer-Aided Manufacturing) program, the wedge width was held constant by 10 μm , the wedge depth (d) was varied to be 10 μm and 20 μm , and the pitch of wedges (p) was controlled to be 20 μm and 30 μm , respectively. The galvanome-

ter was utilized to control the wedge width, depth and pitch with the aid of X-Y stage controller. Four microtextured specimens were prepared for characterization; Texture-I with $d = 10\ \mu\text{m}$ and $p = 20\ \mu\text{m}$, Texture-II with $d = 10\ \mu\text{m}$ and $p = 30\ \mu\text{m}$, Texture-III with $d = 20\ \mu\text{m}$ and $p = 20\ \mu\text{m}$, and Texture-IV with $d = 20\ \mu\text{m}$ and $p = 30\ \mu\text{m}$.

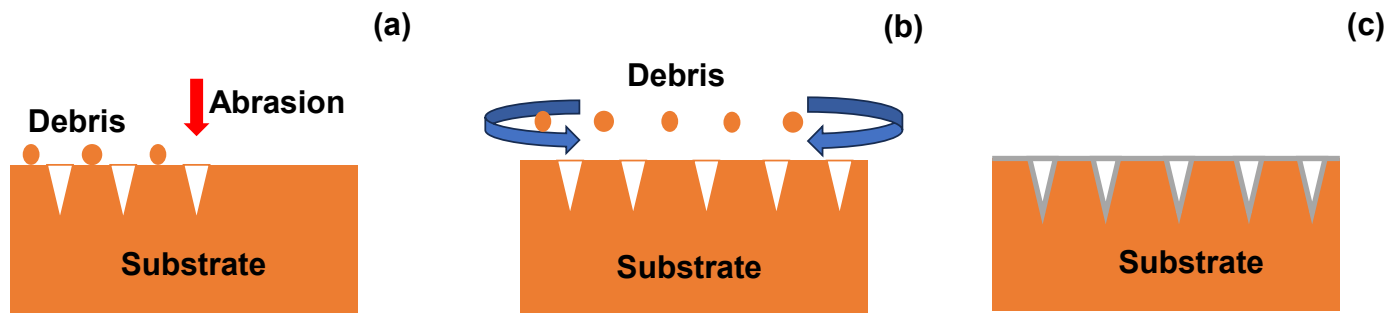


Figure 2. A schematic procedure to fabricate the micro-/nanotextured metallic device for IR-emission. (a) Microtexturing onto the copper plate via the picosecond laser micro-machining, (b) soft-etching to remove the micro-slug or debris particles on the microtextures, and (c) wet-plating to superpose the nickel nanotextures onto the microtextures.

In the following, the machined wedge width, depth and pitch were measured by laser microscopy (Keyence; Tokyo, Japan).

2.3. Soft Etching

A soft etching process was employed to chemically remove the copper debris particles on the laser-machined microtextures, as illustrated in Figure 2b. After degreasing the specimen for 180 s, sodium persulfate and sulfuric acid were mixed and used as an etchant for soft etching process. After soft etching for 335 s, the specimen was cleansed in ultrasonic.

2.4. Nickel Wet-Plating

Wet-plating was utilized to deposit the nanotextured layer onto the copper microtextures, as depicted in Figure 2c. NiCl_2 solution was used as a source of nickel deposits. The total current, the current density, and the chemical solutions influence the nucleation and growth processes to form this nickel nanotextured unit cell. In the following experiments, two types of nickel wet-plating processes were used to form a uniform nickel nanotextured layer after degreasing for 300 s at 333 K, cathodic-electrolytic degreasing by 3.0 V for 60 s at 333 K, anodic-electrolytic degreasing by 3.0 V for 30 s at 298 K; e.g., nickel electric plating by $4\ \text{A}/\text{dm}^2$ for 900 s at 338 K and nickel-tin electric plating by $1\ \text{A}/\text{dm}^2$ for 120 s at 338 K.

Nickel nano-pillars nucleated and grew onto the microtextured unit cell surfaces in the similar dendritic deposition to acicular microtexturing in [7,8]. The application of electric voltage in pulse was optimized to make uniform deposition in the above. The bonding state of nickel acicular nanotextures onto the microtextured surface was compared before and after the convection and boiling heat transfer experiments in [13]. No delamination of nickel nanotextures was detected in SEM observation, which proved that this bonding had sufficient strength even in practical situations.

2.5. Infrared Emissivity Spectrum Measurement

The thermographic microscopy with FT-IR (Shimazu, Co., Ltd., Kyoto, Japan) was utilized for measurement of IR-emissivity. The optical beam line in this system is explained in Figure 3a. Two beams from IR and visible sources are introduced into the Cassegrain objective, which consists of concave primary and convex secondary mirrors. The beam from this objective is selected by an aperture and detected by T2SL (Type II Super-Lattice)

sensor as well as the optical microscope. In the following, the aperture was fixed to be 200 μm although it was controllable to focus the measured area on the microtextured specimen. No significant change was detected in the measured IR-emission spectra even by varying the position and size of apertures.

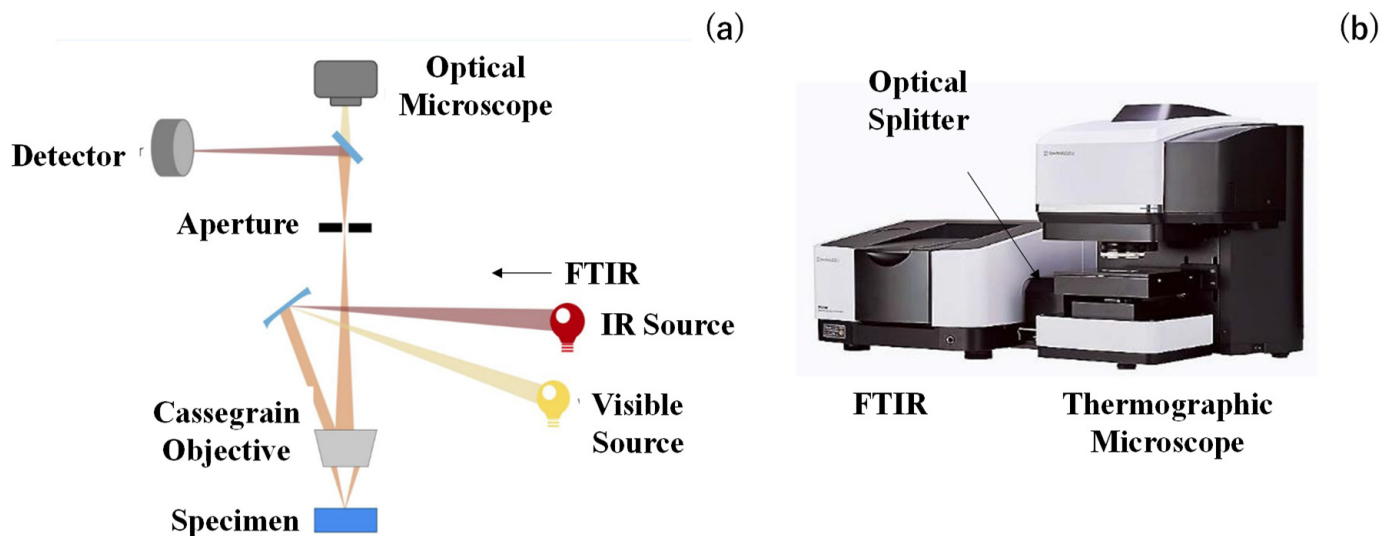


Figure 3. Thermographic microscopy with FT-IR (Fourier Transform InfraRed) unit. (a) A schematic view on the IR-emissivity measurement, and (b) overview on the measurement system.

In practical operation, the thermographic microscope with FTIR in Figure 3b was utilized to measure the IR-emittance spectra for the regularly aligned microtextures as well as the bare copper and nickel-plated smooth sheets.

2.6. Microstructure Analysis

SEM (Scanning Electron Microscopy; JOEL, Tokyo, Japan) was utilized to observe and measure the unit cell of microtextured and nano-/microtextured copper sheets as well as its alignment.

3. Results

Four microtextured copper specimens were fabricated by picosecond laser micromachining. They were further wet-plated to cover their surface structure by nickel nanotextured layer. IR-emission spectra were measured to investigate the effect of micro- and nanotextures on the IR-emissivity.

3.1. Picosecond Laser Microtexturing

Four microtextures were designed and accommodated into the copper sheet as shown in Figure 4a. In Texture-I and II, every unit cell aligned with the pitch of 20 and 30 μm , respectively, in correspondence to the CAM data for laser micromachining. Their depth is fixed to be 10 μm ; each unit cell is connected by shallow linkage in each other. In Texture-III and IV, the unit cell depth was 20 μm . Comparing Texture-I and III, the unit cells in Texture-III are isolated from each other.

The unit cell geometry is compared among four specimens in Figure 4b. The cone-like and cube-like micro-bumps are aligned in a regular way to form microtextures in Texture-I and -II. On the other hand, paraboloidal and cuboidal micro-cones are isolated from each other and aligned regularly to form the microtextures in Texture-III and -IV.

As distinctly seen in Figure 4b, the fine particles or fragments are deposited on the whole unit cell surfaces. These came from the redeposition of debris particles via the

abrasion process during the laser micromachining. The conventional mechanical polishing might be insufficient to clean and polish the affected surface layer by debris particles. The soft etching process was employed to chemically remove these particles and fragments before mechanical polishing.

Figure 5a shows four microtextured specimens after soft etching. Compared to Figure 4a, fine regular alignment of unit cells is more distinctly recognized. In particular, as seen in Figure 5b, each unit cell has fine microtexture surface profiles. The convex bumps and micro-cones are linked with each other through concave microtextures.

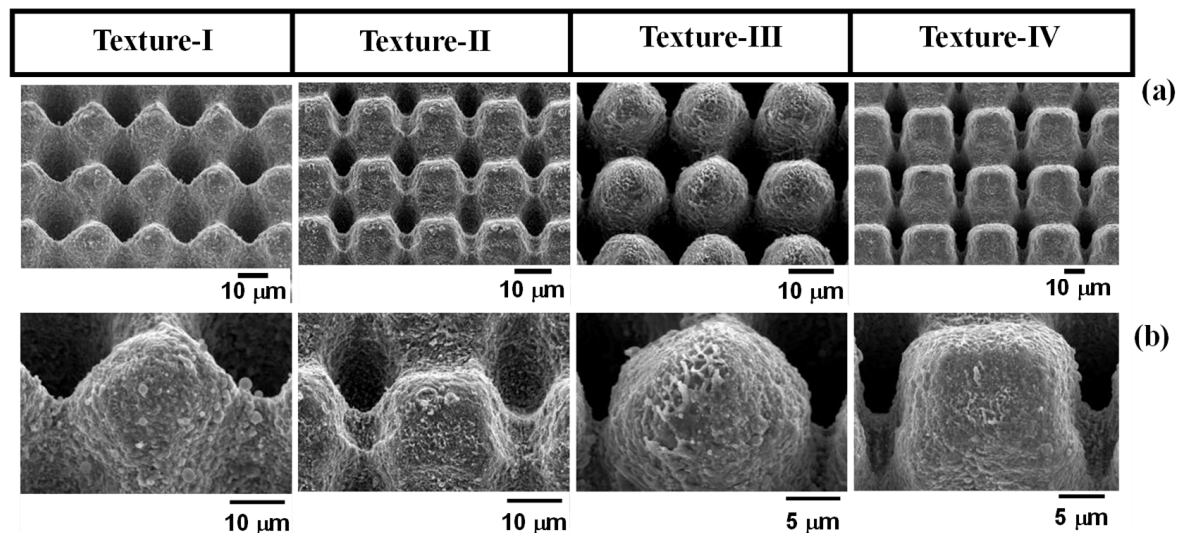


Figure 4. Four microtextured specimens built into the copper sheet by picosecond laser micromachining. (a) Alignment of microtextures formed into the copper sheets, and (b) each unit cell of microtextures.

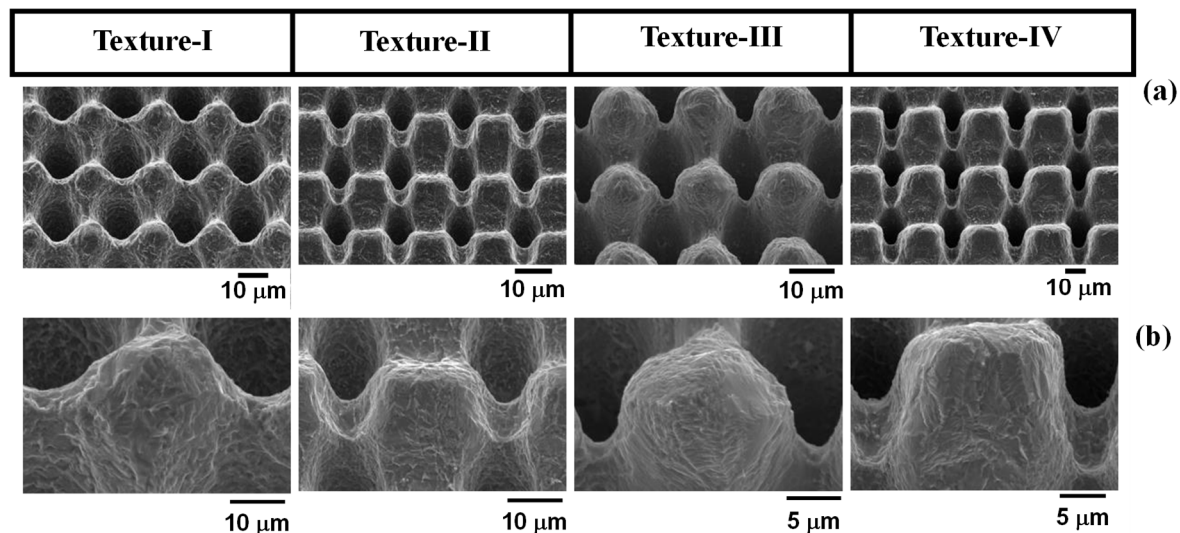


Figure 5. Four laser-microtextured copper specimens after polishing. (a) Alignment of polished microtextures, and (b) unit cell of polished microtextures.

3.2. Nickel Wet-Plating

The nickel wet-plating process was utilized to form a nanotextured nickel layer onto each convex and concave surface of microtextures. Figure 6a depicts the formation of nanotextured nickel layer onto these four microtextured specimens. Compared to Figure 5a, the whole microtextured surfaces were covered by a thin layer with acicular dots.

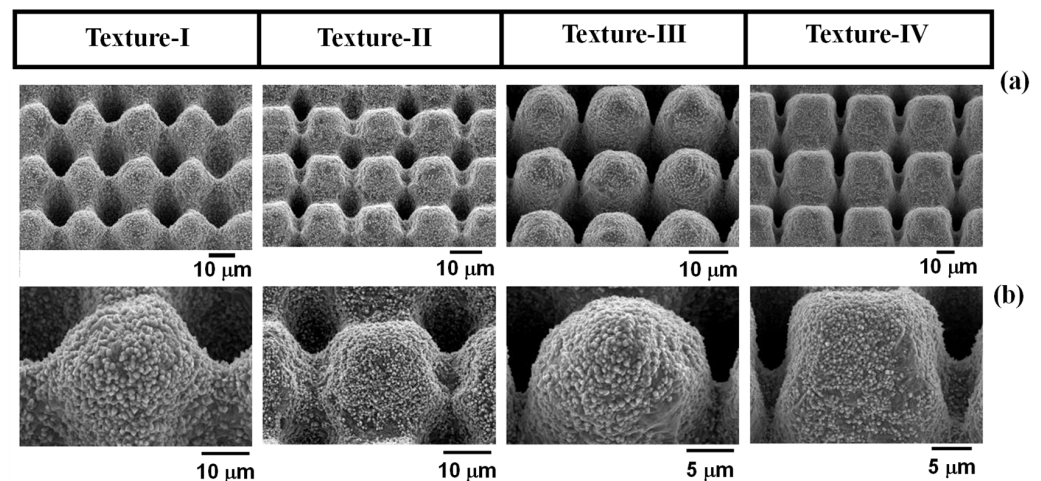


Figure 6. Four nickel-plated nanotexturing onto microtextured copper specimens. (a) Alignment of micro-/nanotextured copper specimen, and (b) unit cell of these micro-/nanotextured copper specimen.

Figure 6b shows the deposition of nickel nanotextures onto each surface of unit cells. The nickel nanotextures nucleate on every spot on the polished copper surface as seen in Figure 5b. They grow to form a layer while a new nanotexture nucleates onto this layer. Hence, the nickel nanotexture looks like an acicular layer growing on each unit cell surface in Figure 6b.

The cross-section of micro-/nanotextured specimen for Texture-I was analyzed by SEM to describe the nanotextured layer through the nucleation and growth of nickel deposits during the wet-plating. As stated in Figures 4a, 5a and 6a, all convex microtextures in Texture-I are linked with each other through the concave surfaces. As shown in Figure 7a, A-part corresponds to a convex microtexture and B-part represents a concave area. To be discussed later, the deposition process becomes different on the convex and concave surfaces. As depicted in Figure 7b, the cross-sectional view of nanotextured convex surfaces consists of the uniform layer with the thickness of 2 µm and the acicular nanotextures onto the layer. On the other hand, as seen in Figure 7c, the bottom of valley on the concave surfaces has nearly the same geometric configuration as seen in Figure 7b. On the side surfaces of concave parts, no acicular deposits were detected but nanotextures are formed in the uniform nickel layer.

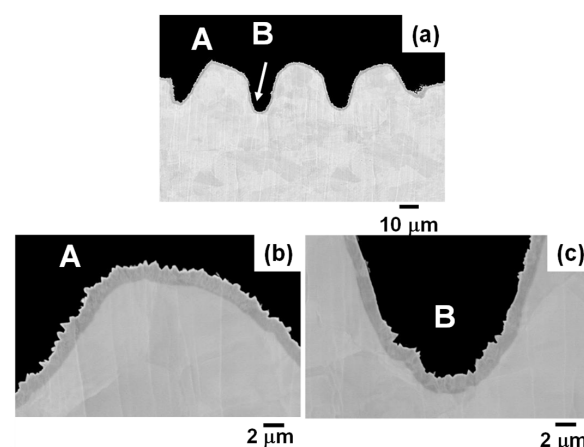


Figure 7. Formation of nanotextured layer onto the microtextured copper sheet. (a) Cross-sectional view of micro-/nanotextured copper specimen, (b) formation of nanotextured layer onto the convex part of microtextured copper specimen, and (c) formation of nanotextured layer onto the concave part of microtextured copper specimen.

3.3. IR-Emissivity

IR-emissivity spectrum was measured by thermographic microscopy with FT-IR in the wavelength (λ) range from $\lambda = 2 \mu\text{m}$ to $\lambda = 14 \mu\text{m}$. At first, the IR-emissivity of bare smooth copper sheet, or $I(\text{Cu}; \lambda)$, was measured as a reference. As shown as a square symbol in Figure 8, $I(\text{Cu}; \lambda) \sim 0.0$ in the whole wavelength range; e.g., the maximum intensity is less than 2×10^{-3} . This low emissivity simply characterizes the IR optical performance of the polished copper sheet. In fact, as listed in [14], the emissivity at $\lambda = 1.6 \mu\text{m}$ is 0.03, and it becomes much less for $8 \mu\text{m} < \lambda < 14 \mu\text{m}$ in the case of the polished copper sheet. That is, $I(\lambda) \sim 0$ for smooth metallic surface in the whole IR range. In second, IR-emissivity of nickel nanotextured copper sheet, or $I(\text{Ni-nanotextured-Cu-Sheet}; \lambda)$, was also measured as a reference. As compared to $I(\text{Cu}; \lambda)$ in Figure 8, $I(\text{Ni-nanotextured-Cu-Sheet}; \lambda) \sim I(\text{Cu}; \lambda) \sim 0$ for $\lambda > 7 \mu\text{m}$. To be noticed, this IR-emissivity monotonously increases with decreasing λ from $\lambda = 7 \mu\text{m}$ down to $2 \mu\text{m}$. As stated in [15], the surface roughness enhances the emissivity spectrum; however, monotonic increase with decreasing λ is never explained by surface profile effect on the emissivity. This enhancement of emissivity might come from light trapping via the interaction between the plane waves and the nanostructures as stated in [16]. The acicular nanotextures on the microtextures interact with the waves traveling along these nanotextures to enhance the optical emissivity in the shorter wavelengths.

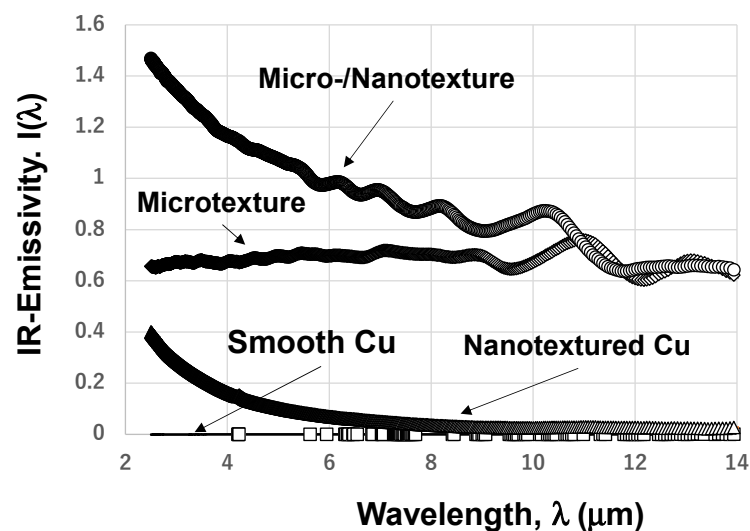


Figure 8. Comparison of IR-emission spectra among the bare copper sheet, the nickel wet-plated copper sheet, the laser microtextured copper sheet after cleansing, and the nickel-plated and laser microtextured copper sheet.

In third, IR-emissivity or $I(\text{Microtextured-Cu}; \lambda)$ was measured and depicted in Figure 8 for the microtextured copper specimen of Texture-I after soft etching. This $I(\text{microtextured-Cu}; \lambda)$ is nearly constant by 0.7 irrespective of the wavelength. At each resonant wavelength, this emissivity spectrum has higher intensity than the average. Furthermore, IR-emissivity was also measured for micro-/nanotextured copper sheet and compared to other spectra in Figure 8. Higher intensity is attained to be 0.8 to 0.85 for $\lambda < 11 \mu\text{m}$; due to light trapping, $I(\text{micro-/nanotexture}; \lambda)$ becomes more than 1.0 for $\lambda < 7 \mu\text{m}$. Due to the limit of emissivity by Kirchhoff's law, emissivity could never exceed 1.0 if every measured behavior is abided by the gray-body radiation.

After [16], this excess of measured emissivity is attributed to light-trapping in the short wavelength range. Let us subtract the light-trapping effect from the measured spectrum, $I(\text{micro-/nanotexture}; \lambda)$, as a simple model to deduce the IR-emissivity without light trapping for $\lambda < 7 \mu\text{m}$. That is, $I(\text{micro-/nanotexture}; \lambda)$ was modified to be $I(\text{Texture-}$

$I; \lambda$) by $I(\text{Texture-I}; \lambda) = I(\text{micro-/nanotexture}; \lambda) - I(\text{Ni-nanotextured-Cu-Sheet}; \lambda)$ for the whole wavelength range. The modified IR-emissivity spectrum for Texture-I is shown in Figure 9. Except for the experimental error for $\lambda < 3 \mu\text{m}$, the absolute intensity decreases linearly with λ . To be discussed later, this linear decay does not only come from the small surface roughness on the softly etched copper microtextures but also from the morphological profile of nickel nanotextures in alignment. The resonance sub-peaks to microtextures superpose onto this linear decay. As seen in Figure 5a,b, the unit cell of Texture-I with the depth of $10 \mu\text{m}$ has several resonance at the specified wavelengths in correspondence to these sub-peaks.

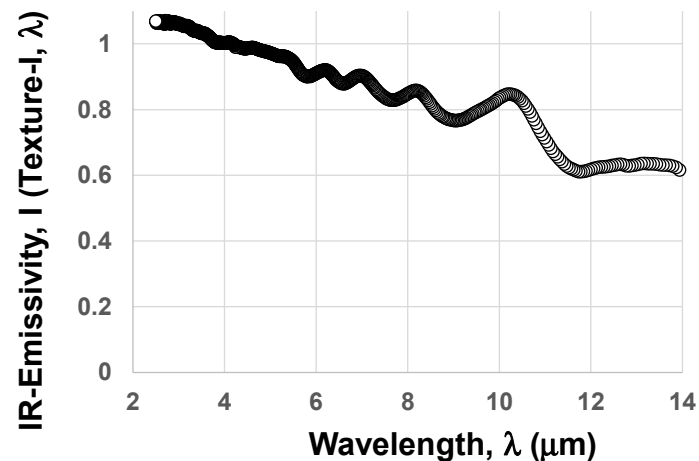


Figure 9. A modified IR-emissivity spectra for Texture-I specimen or $I(\text{Texture-I}; \lambda)$ for the wavelength range from $\lambda = 2 \mu\text{m}$ to $\lambda = 14 \mu\text{m}$.

The effect of microtexture profile in Figure 5 on the IR-emissivity is described by comparison of each measured IR-spectrum in Figure 10. Except for the resonance at the selected wavelengths, the average emissivity intensity becomes nearly constant in the whole wavelength range; e.g., $I(\text{Texture-I}; \lambda) \sim 0.65$, $I(\text{Texture-II}; \lambda) \sim 0.6$, $I(\text{Texture-III}; \lambda) \sim 0.8$, and $I(\text{Texture-IV}; \lambda) \sim 0.65$. This proves that surface roughness of microtextured unit cells has nothing to do with IR-emissivity, and that their geometry has influence on the resonant and intensity of emissivity.

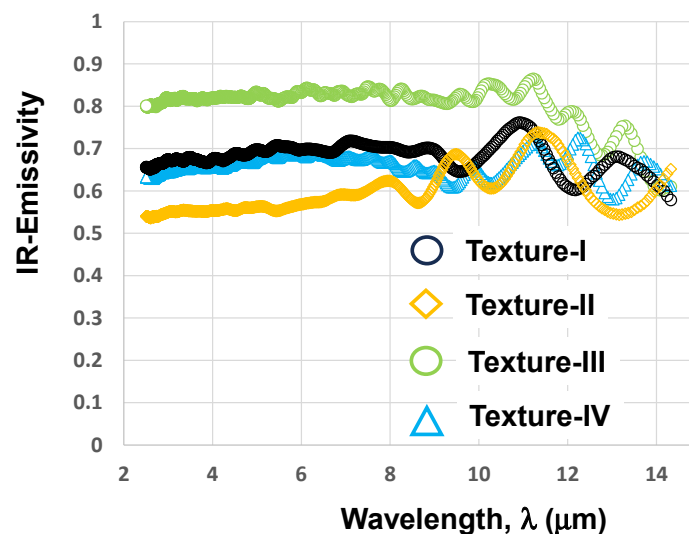


Figure 10. Comparison of IR-emissivity spectra among four microtextured specimens after soft etching for the wavelength range from $\lambda = 2 \mu\text{m}$ to $\lambda = 14 \mu\text{m}$.

Let us consider the effect of unit cell dimensions on this constant intensity in Figure 10. Comparing the IR-spectra for Texture-I and II, wider pitch in regular alignment of unit cells results in lowering the emissivity in the near-IR range. This is because the wider pitches work as a disturbance to more homogeneous unit cell alignment. Comparing the IR-spectra between Texture-I and III, the cone-shaped, deeper unit cell induces much higher intensity in IR-emission. Anisotropic unit cell geometry is effective to enhance the IR-emission intensity. In addition to IR-emission intensity in average, more resonance peaks are detected in Texture-III than in Texture-I. More concave and convex substructures are detected on the unit cell surface in the Texture III to induce more resonance intensities to far-IR waves.

Figure 11 compares the IR-emission spectra of four micro-/nanotextured specimens after adjustment by $I(\text{micro-/nanotexture}; \lambda) - I(\text{Ni-nanotextured-Cu-Sheet}; \lambda)$ for each specimen. The linear decay of emission intensity with λ is commonly noticed in these spectra. This comes from the surface profile of nanotextures. The acicular nanotextures on the convex microtextures surface play a role in keeping high intensity in the near-IR region. With increasing λ , this role reduces by itself since the concave microtextured surface area with a thin nanotextured film has more influence on the IR-emissivity toward far IR-range. In fact, relatively high emissivity is preserved in case of Texture-III specimen with deeper microtextures and narrower pitch in alignment, where a concave microtextured surface area ratio is less than the one in Texture-I, -II and -IV, as shown in Figure 5.

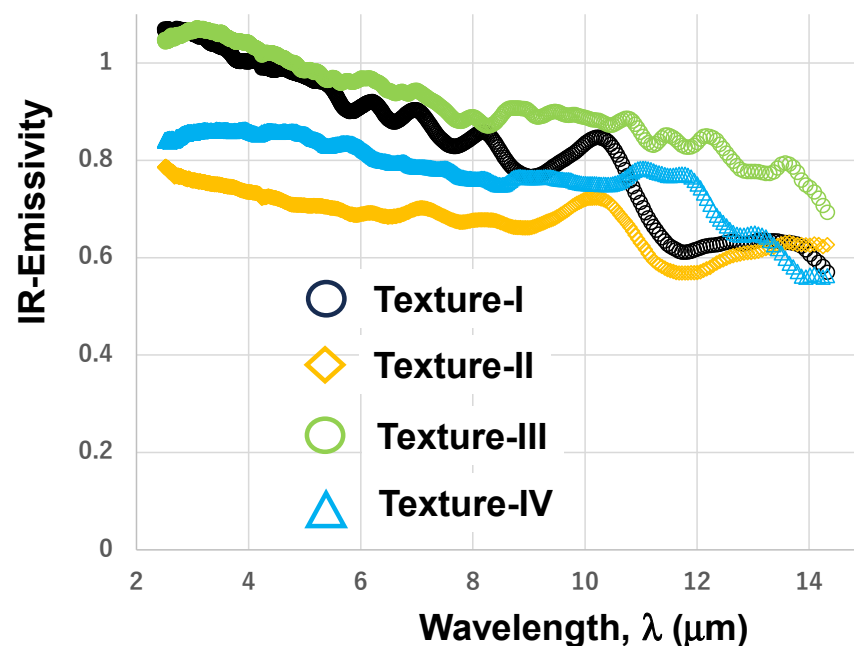


Figure 11. Comparison of IR-emissivity spectra among four micro-/nanotextured specimens after data editing for the wavelength range from $\lambda = 2 \mu\text{m}$ to $\lambda = 14 \mu\text{m}$.

4. Discussion

In the present approach to fabricate the metallic IR-emission devices, both micro- and nanotextures have a capacity to improve the IR-emissivity in the wide wavelength range. Let us summarize the IR-emission data of four specimens with different d and p in Table 1. The depth and pitch of unit cells have much influence on the IR-emission intensity and the wavelength range with constant intensity.

Table 1. Comparison of the IR-emission data among four microtextured copper devices with and without nickel nanotextures.

Microtextured Device	Texture-I	Texture-II	Texture-III	Texture-IV
d and p	10 μm /20 μm	10 μm /30 μm	20 μm /20 μm	20 μm /30 μm
I (microtextures)	0.65	0.6	0.8	0.65
I (micro/nano)	0.8	0.7	0.9	0.8
Wavelength limit for constant intensity	14 μm	12 μm	14 μm	12 μm

IR-emission intensity is around 0.95 for $2\ \mu\text{m} < \lambda < 5\ \mu\text{m}$ for nano-photonic and meta-material devices.

In particular, when using the micro-corn-shaped copper microtextures together with nickel acicular nanotextures, higher IR-emissivity than 0.9 is attained in wider wavelength range than that reported in the literature [9,10,15]. Although their IR-emissivity reached 0.95 or more in the limited wavelength range of $2\ \mu\text{m} < \lambda < 5\ \mu\text{m}$, a large-area device with sufficient engineering durability could never be made from their nano-photonic materials, meta-materials and silicon [9,10,15]. The present metallic device is made from copper sheet with nickel layer; this is adaptive to large-area radiation application in air or in space [17,18].

In the wavelength range for $\lambda < 2\text{--}3\ \mu\text{m}$, the spectral emissivity was discussed on the surface roughness effect [15]. As estimated, the emissivity intensity varies with the wavelength with dependency on the surface roughness profile. However, as seen in Figure 10, the intensity of emissivity is constant in insensitive to wavelength in the near-IR range. This constant intensity is affected by the depth and pitch of unit cells of microtextures in Figure 5. Among four microtextured unit cells, the micro-cone-like-shaped, deeper unit cell induces the highest IR-emission intensity. On the other hand, the resonance of IR-emissivity is enhanced in the far-IR range for $\lambda > 10\ \mu\text{m}$ in every specimen. In particular, when using deeper microtextures with narrow pitch in alignment, more resonance peaks are distinctly detected. The characteristic surface profile of each unit cell in microtextures results in this resonance of IR-emission in the similar manner as reported in [6–8]. As discussed in [16], high IR-emission intensity in broader band of wavelength must be characteristic to the continuous IR-resonance to microtextured device with deeper wedge and narrower pitch.

This microtexture effect on the IR-emissivity is further modified by nanotexturing onto the microtextured unit cell surface. After the nucleation and growth mechanism [19], a nickel deposit nucleates on the microtextured unit cell surfaces and grows to a thin film. As seen in Figure 7b, the deposition probability is thought to be uniform so that the acicular nanotextures homogeneously distribute on the convex surfaces. On the concave surfaces, the deposition probability decreases from their top to bottom so that the nanotextures are formed to be a thin film at their bottom. This difference in the surface morphology by nanotexturing may have influence on the IR-emissivity. With deepening the microtexture profile and narrowing the pitch in alignment, the IR-emission is much enhanced by nanotextures on the convex surfaces of microtextures.

The superposition of nanotextures onto the microtextured surfaces is performed in various methods. Among them, LIPSS (Laser-Induced Periodic Surface Structuring) is effective to control the surface properties of metallic sheets and plates, as stated in [20,21]. Their hydrophilic surface was modified to be superhydrophobic by these LIPSS-nanogrooves onto the laser-machined microtextured surfaces. In the LIPSS-based superposition, these nanogrooves are aligned onto the microtextured surfaces with intrinsic directivity to each

microtexture. In the present acicular nanotexturing, the convex microtextured surfaces are superposed by acicular deposits onto the nickel layer, and the concave surfaces are covered by thin nickel layer. This weakly modulated nanotexture profile is changed to a nanostructured surface with anisotropic directivity using the LIPSS. This morphologic change in nanotexturing by LIPSS has influence on the linear decay of IR-emissivity with λ , as shown in Figure 11. That is, the role of thin nickel-layered surfaces in the IR-emission is enhanced from middle to far-IR range.

As compared in Table 1, nearly 100% IR-emissivity was attained for $2\ \mu\text{m} < \lambda < 4\ \mu\text{m}$ using the nano-photonic and meta-material devices. As depicted in Figures 10 and 11 for Texture-III specimen, 80% IR-emissivity intensity is attained by microtexturing the copper sheet, and 95 to 100% IR-emissivity is also obtained by micro-/nanotexturing. That is, nearly the same high IR-emissivity as attained by nano-photonic and meta-material devices is also achieved by metallic surface-texturing control.

In the present study, the nickel nanotextures are deposited onto the copper microtextured surface to enhance the IR-emissivity. These metallic microtextures can be modified to a composite of copper and its oxide phases. In the nanotexturing step, the nickel is also modified to iron–nickel or nickel–tin alloys. This composite material design is also available in this micro-/nanotexturing approach, as suggested in [22].

This micro-/nanotextured copper sheet is available as a heat radiation device to make thermal spreading from heat source in large surface areas such as solar panels and giant antennae [17,18]. As shown in Figure 10, the microtextured unit cell with much depth and narrow pitch is joined to the heat source for efficient heat radiation. As stated in [23], higher heat flux is transported to the target specimen using the IR-emission device with the average intensity of 90% or more. The IR-device is designed to have corn- and cuboid-shaped microtextures and the nanotextured acicular deposits. This micro-/nanotextured device also works as an anti-reflection (AR) film onto the infrared lens for night-vision devices [24] and for thermographic camera [25]. The microtextured assembly of cone-shaped, tall unit cells with regular alignment by narrow pitch is effective to significantly control the refractive index of IR-waves through the IR-lenses as theoretically estimated in [26].

5. Conclusions

The micro-/nanotexturing is utilized to fabricate the copper-base sheet device for IR-emission with high intensity in the wavelength range from $2\ \mu\text{m}$ to $14\ \mu\text{m}$. The depth of unit cells and pitch in alignment are varied to describe their effect on the IR-emission spectra. The micro-cone-shaped unit cells with sufficient height in regular alignment with narrower pitch yields the higher IR-emission intensity than 0.9, even in far-IR range. In different from the nano-photonic and meta-materials device, this micro-/nanotextured copper base device is utilized for heat radiation process in a large area and for thermal spreading to heat pipes and structural components. This metallic device has sufficient engineering durability to be working in air or in water.

Author Contributions: Conceptualization, T.A. and H.N.; methodology, T.A., H.N. and T.N.; software, T.A. and T.N.; validation, T.A., H.N. and T.N.; formal analysis, T.N.; investigation, T.A., H.N. and T.N.; resources, H.N.; data curation, T.A. and T.N.; writing—original draft preparation, T.A.; writing—review and editing, H.N.; supervision, H.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are available for future research under mutual understanding agreement.

Acknowledgments: The authors would like to express their gratitude to Mitohka (Okayama Prefectural Industrial Technology Center) for his help in laser micromachining.

Conflicts of Interest: Author Hiroki Nakata and Takeshi Nasu are employed by the company Ebinax, Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. MaKinsey and Company. How Data Centers and Energy Sector Can Sate AL'S Hunger for Power. Available online: <https://www.mckinsey.com/industries/private-capital/our-insights/> (accessed on 7 August 2025).
2. Yuan, X.; Liang, Y.; Hu, X.; Xu, Y.; Chen, Y.; Kosonen, R. Waste heat recoveries in data centers: A review. *Renew. Sustain. Energy Rev.* **2023**, *188*, 113777. [CrossRef]
3. Nehme, C. *Thermal Interface Materials: Enhancing Heat Transfer in Modern Systems*; Amazon Digital Services LLC: Seattle, WA, USA, 2024.
4. Nair, V.; Baby, A.; Anoop, M.B.; Indrajith, S.; Murali, M.; Meenakshi, B.N. A comprehensive review of air-cooled heat sinks for thermal management of electronic devices. *Int. Commun. Heat Mass Transf.* **2024**, *159*, 108055. [CrossRef]
5. Chen, Z.; Hu, J.; Zhang, Z.; Li, J.; Zhang, G.; Han, F. Gradient distribution surface texture for enhancing the surface heat transfer performance of the mini-channel. *Appl. Therm. Eng.* **2025**, *270*, 126237. [CrossRef]
6. Kohiyama, A.; Shimizu, M.; Yugami, H. Unidirectional radiative heat transfer with a spectrally selective planar absorber/emitter for high-efficiency solar thermophotovoltaic systems. *Appl. Phys. Express* **2016**, *9*, 112302. [CrossRef]
7. Aizawa, T.; Nakata, H.; Nasu, T. Infrared emission for heat radiation from micro-cone textured metallic sheet device with semi-regular alignment. *ASME J. Micro Nano-Manuf.* **2023**, *11*, 021003. [CrossRef]
8. Aizawa, T.; Nakata, H.; Nasu, T. Laser micromachining for the nucleation control of nickel microtextures for IR emission. *Micromachines* **2025**, *16*, 696. [CrossRef] [PubMed]
9. Li, W.; Fan, S. Nano-photonic control of thermal radiation for energy applications. *Opt. Express* **2018**, *26*, 15995–16021. [CrossRef] [PubMed]
10. Tian, Y.; Ghanekar, A.; Ricci, M.; Hyde, M.; Gregory, O.; Zheng, Y. A Review of tunable wavelength selectivity of meta-materials in near-field and far-field radiative thermal transport. *Materials* **2018**, *11*, 862. [CrossRef] [PubMed]
11. Misyura, S.Y.; Strizhak, P.A.; Volkov, R.S.; Morozov, V.S. The influence of the wall microtexture on functional properties and heat transfer. *J. Mol. Liq.* **2019**, *294*, 111670. [CrossRef]
12. Shani, N.; Shakya, A.K.; Cheng, F.; Shuvayev, V.; Deych, L.; Carmon, T. Observation of spectrally continuous enhancement by mode coalescence. *Opt. Express* **2025**, *33*, 31722–31730. [CrossRef] [PubMed]
13. Gregorius, A.S.P.; Sasaki, S.; Hayashi, S.; Aizawa, T.; Ono, N. Relationship between heat flux and bubble population density in heat transfer enhancement of flow boiling using microtextured surfaces. *J. Therm. Sci. Technol.* **2024**, *19*, 23-00517. [CrossRef]
14. List of Metals Emissivity. Available online: <https://www.flukeprocessinstruments.com/en-us/service-and-support/knowledge-center/infrared-technology/emissivity-metals> (accessed on 14 August 2025).
15. Zhang, Z.; Chen, M.; Zhang, L.; Li, H.; Huang, H.; Zhang, Z.; Yu, P.; Niu, Y.; Gao, S.; Wang, C.; et al. A straightforward spectral emissivity estimating method based on constructing random rough surfaces. *Light-Sci. Appl.* **2023**, *12*, 266. [CrossRef] [PubMed]
16. Anguita, J.V.; Ahmad, M.; Haq, S.; Allam, J.; Silva, S.R.P. Ultra-broadband light trapping using nanotextured decoupled graphene multilayers. *Sci. Adv.* **2016**, *2*, e1501238. [CrossRef] [PubMed]
17. Zhe, L.W.; Yusoff, M.I.; Iwanto, M.; Razak, A.; Ibrahim, S.; Zhubir, N.S. Investigation of solar panel performance based on different wind velocity using ANSYS software. *J. Electr. Eng.* **2026**, *1*, 456–463. [CrossRef]
18. Dbouk, T.; Mourad, O. A review on thermal management and heat dissipation strategies for 5G and 6G base stations: Challenges and solutions. *Energies* **2025**, *18*, 1355. [CrossRef]
19. Lewis, N. Nucleation and growth theory. In *Crystal Growth*, 2nd ed.; Pergamon Press: Oxford, UK, 1980; Chapter 2, pp. 23–63.
20. Aizawa, T.; Inohara, T.; Wasa, K. Femtosecond laser micro-/nano-texturing of stainless steels for surface property control. *Micromachines* **2019**, *10*, 512. [CrossRef] [PubMed]
21. Aizawa, T.; Inohara, T.; Wasa, K. Fabrication of hydrophobic stainless steel nozzles by femtosecond laser micro-/nano-texturing. *Int. J. Autom. Technol.* **2020**, *14*, 159–166. [CrossRef]
22. Mink, J.; Mihaly, J.; Nemeth, C.; Nemeth, P.; Drees, M.; Lokshin, B.V.; Wolf, M.; Butler, I.S.; Hajiba, L. Preparation and characterization by infrared emission spectroscopy and applications of new mineral-based composite materials of biomedical interest. *Appl. Spectro. Rev.* **2018**, *53*, 439–485. [CrossRef]
23. Emanuel, M. Heat Transfer by Infrared Radiation from Sensor to Sample. Available online: <https://ctherm.com/resources/newsroom/thermal-conductivity/heat-transfer-by-ir/> (accessed on 14 August 2025).
24. NUSTL. *Night Vision Devices Assessment Report*; NUSTL: New York, NY, USA, 2024.

25. Korukçu, M.Ö.; Kilic, M. The usage of IR thermography for the temperature measurements inside an automobile cabin. *Int. Comm. Heat Mass Transf.* **2009**, *36*, 872–877. [[CrossRef](#)]
26. Brewer, J.; Kulkmi, S.; Raman, A.P. Resonant anti-reflection metasurfaces for infrared transmission optics. *Nano Lett.* **2023**, *23*, 8940–8946. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.