

National Aerospace Laboratories

Engineered Ge/MgF_2 Multilayer Thin-Film Emitter for Infrared Stealth and Radiative Cooling.....

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Design and Optimization of a Ge/MgF₂ Multilayer Thin-Film Emitter for Infrared Stealth and Passive Radiative Cooling

1. Introduction

The rapid advancement of infrared (IR) detection technology has imposed stringent requirements on the thermal management and signature control of military and aerospace platforms. Modern thermal imaging systems operating in the mid-wave infrared (MWIR, 3–5 μm) and long-wave infrared (LWIR, 8–14 μm) atmospheric transmission windows can detect the thermal signatures of targets at standoff distances exceeding several kilometres [2]. The radiated power of any surface is governed by the Stefan–Boltzmann law, $P = \varepsilon\sigma T^4$, where ε is the hemispherical emissivity and T is the absolute surface temperature, so even modest emissivity reductions in the detection bands significantly lower detectability.

Conventional broadband low-emissivity coatings suppress thermal emission uniformly across 3–14 μm [3]. While effective at reducing IR signature, this approach creates a fundamental thermal management conflict: suppressing emission across all wavelengths inhibits the natural heat dissipation of the surface, causing heat accumulation that degrades structural integrity, electronic performance, and operational survivability [4]. This tension has motivated *spectrally selective* strategies that suppress emission only within the atmospheric windows, while permitting or enhancing emission in the non-atmospheric window (5–8 μm) where outgoing radiation is absorbed by the atmosphere before reaching IR sensors, thereby enabling simultaneous IR stealth and passive radiative cooling.

In this work, a novel all-dielectric spectrally selective emitter comprising four alternating MgF₂/Ge thin-film bilayers deposited on a 25 μm SiO₂ substrate is designed and characterised using full-wave finite-element simulations in COMSOL Multiphysics 6.4. The high refractive-index contrast between Ge ($n = 4.003$) and MgF₂ ($n = 1.350$) produces a one-dimensional photonic bandgap that reflects radiation in both atmospheric windows, while the SiO₂ phonon resonance at 7–9 μm drives selective thermal emission in the 5–8 μm cooling window. The structure achieves Planck-weighted emissivities of $\bar{\varepsilon}_{3-5} = 0.043$, $\bar{\varepsilon}_{5-8} = 0.646$, and $\bar{\varepsilon}_{8-14} = 0.041$, with a figure of merit $\text{FOM} = 0.80$ and a peak spectral emissivity of 0.935 at $\lambda = 6.9 \mu\text{m}$.

2. Literature Review

Significant research effort has been directed towards spectrally selective emitters for simultaneous IR stealth and radiative cooling. Earlier work focused on broadband low-emissivity metallic coatings, which suppress IR radiation uniformly but create unacceptable thermal management trade-offs [3]. The spectrally selective approach emerged as a systematic solution: by engineering the spectral emissivity profile rather than the total

emissivity, a structure can be simultaneously “cold” in the detection bands and “hot” in the non-atmospheric window.

Zhang et al. [8] demonstrated a Ge/ZnS one-dimensional photonic crystal achieving average emissivities of 0.046 and 0.19 in the MWIR and LWIR windows respectively, with a non-atmospheric emissivity of 0.579 — the first experimental validation of the photonic bandgap approach for IR stealth. Pan et al. [9] proposed a Si/Ge₂Sb₂Te₅/Au metamaterial achieving emissivities of 0.17, 0.69, and 0.13 in the three bands; however, the requirement for lithographic patterning of the GST phase-change layer limits large-area scalability. Peng et al. [10] designed an Ag/Ge planar multilayer with improved atmospheric-window suppression, though silver’s susceptibility to oxidation above 200°C limits deployment on high-temperature platforms.

All-dielectric designs have attracted growing interest for their fabrication simplicity and thermal robustness. Zhou et al. [11] demonstrated an Ag/MgF₂ wavelength-selective metasurface with FOM = 0.78, while Fu et al. [13] reported a ZnS/Ge/CdO multilayer with FOM = 0.82. The most advanced all-dielectric design to date is the Si/HfO₂/SiO₂ nine-layer stack of Li et al. [1], achieving $\bar{\epsilon}_{3-5} = 0.06$, $\bar{\epsilon}_{5-8} = 0.84$, and $\bar{\epsilon}_{8-14} = 0.11$ with FOM = 0.88 — the current state of the art.

Despite these advances, challenges persist: noble-metal designs oxidise above 200°C; phase-change designs require multi-step lithography; and no published all-dielectric design has achieved $\bar{\epsilon}_{3-5} < 0.05$ and $\bar{\epsilon}_{8-14} < 0.05$ simultaneously. The present work addresses these gaps through the Ge/MgF₂ material pair, whose index contrast $\Delta n = 2.653$ is among the largest available for mid-IR transparent dielectrics, enabling strong dual-band suppression with only eight alternating layers and no lithographic patterning. Table 1 compares key literature results alongside the present work.

Table 1 Comparison of representative spectrally selective infrared stealth emitters reported in the literature. The figure of merit (FOM) is defined in Eq. (51).

Technology	$\bar{\epsilon}_{3-5}$	$\bar{\epsilon}_{5-8}$	$\bar{\epsilon}_{8-14}$	FOM	Thermal Robustness	Fabrication	Scalability
Ag/MgF ₂ [11]	0.11	0.66	0.09	0.78	Oxidation above 200°C	Thin-film deposition	High
ZnS/Ge/TiO ₂ /GST/Ag [12]	0.22	0.65	0.16	0.73	Thermally stable	Multi-step lithography	Moderate
ZnS/Ge/CdO [13]	0.07	0.73	0.13	0.82	Thermally stable	Thin-film deposition	Moderate
Si/HfO ₂ /SiO ₂ [1]	0.06	0.84	0.11	0.88	Thermally stable	Requires active emitter integration	Moderate
Ge/MgF₂/SiO₂ (This Work)	0.043	0.646	0.041	0.80	No metal oxidation	Lithography-free deposition	High

3. Operating Principles

3.1 Infrared Spectrum

Infrared radiation occupies the region of the electromagnetic spectrum between visible light and microwaves, extending approximately from $0.75 \mu m$ to $1000 \mu m$. For thermal imaging applications, the infrared spectrum is commonly divided into Near Infrared (NIR), Short-Wave Infrared (SWIR), Mid-Wave Infrared (MWIR), Long-Wave Infrared (LWIR), and Far Infrared (FIR), with MWIR ($3 - 5 \mu m$) and LWIR ($8 - 14 \mu m$) being the most important bands for infrared cameras.

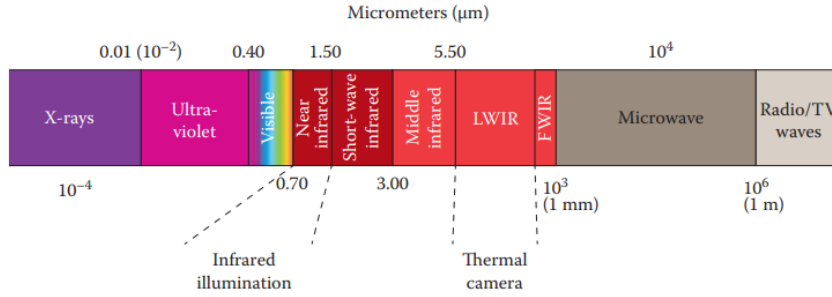


Figure 1 Different camera technologies work in different ranges of the spectrum of light.

3.2 Kirchhoff's Law of Thermal Radiation

The operation of an infrared camera is primarily based on three fundamental physical principles:

1. **Blackbody Radiation (Planck's Law):** Every object with a temperature above absolute zero emits electromagnetic radiation. The intensity and spectral distribution of this radiation depend on the object's temperature. The spectral radiance of an ideal blackbody, a perfect absorber and emitter, is given by Planck's law [5]:

$$E_{b\lambda}(\lambda, T) = \frac{2\pi h_p c^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{h_p c}{k_B \lambda T}\right) - 1}, \quad (1)$$

where $h_p = 6.626 \times 10^{-34} \text{ J s}$ is the Planck constant, $c = 2.998 \times 10^8 \text{ m s}^{-1}$ is the speed of light in vacuum, $k_B = 1.381 \times 10^{-23} \text{ J K}^{-1}$ is the Boltzmann constant, λ is the free-space wavelength, and T is the absolute temperature. A real surface emits a fraction $\varepsilon(\lambda)$ of the blackbody radiance at each wavelength.

2. **Wien's Displacement Law:** The wavelength at which the emitted radiation is maximum shifts with temperature. Objects at room temperature emit most strongly in the long-wave infrared region.

3. **Stefan–Boltzmann Law:** The total thermal energy emitted by an object increases rapidly with temperature and is proportional to the fourth power of its absolute temperature.

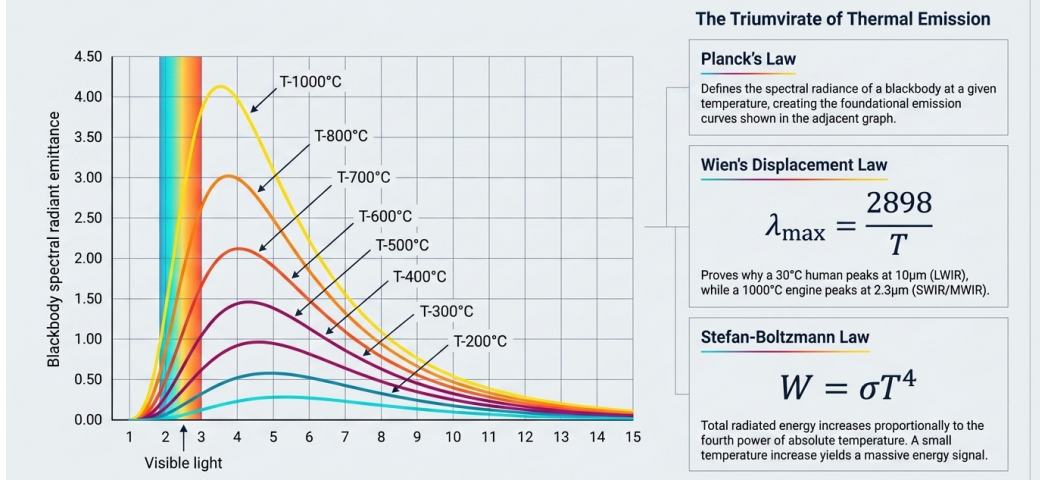


Figure 2 Fundamental Principles : the physics of thermal radiation

These principles establish the relationship between an object's temperature and the infrared radiation detected by the camera, forming the basis of thermal imaging.

Kirchhoff's law states that, for a body in local thermal equilibrium, the spectral emissivity equals the spectral absorptance at every wavelength [5]:

$$\varepsilon(\lambda) = \alpha(\lambda) = 1 - R(\lambda) - \mathcal{T}(\lambda), \quad (2)$$

where $R(\lambda)$ is the spectral reflectance and $\mathcal{T}(\lambda)$ is the spectral transmittance. In the simulations presented here, $R(\lambda)$ and $\mathcal{T}(\lambda)$ are extracted directly from the port S -parameters in COMSOL, and $\varepsilon(\lambda)$ is computed from (2) without further assumptions.

The Planck-weighted average emissivity in a spectral band $[\lambda_1, \lambda_2]$ is defined as [1]:

$$\bar{\varepsilon} = \frac{\int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda) E_{b\lambda}(\lambda, T) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{b\lambda}(\lambda, T) d\lambda}, \quad (3)$$

where the Planck function $E_{b\lambda}$ provides the physically correct weighting that reflects the relative contribution of each wavelength to the total radiated power at temperature T . All band-averaged emissivities in this work are computed at $T = 300$ K using (3) with numerical trapezoidal integration over the COMSOL wavelength-sweep data.

3.3 Absorption, Reflection and Transmission of Infrared Radiation

When infrared radiation falls on a material surface, the incident energy is generally divided into three parts: absorbed energy, reflected energy, and transmitted energy. According

to the law of conservation of energy,

$$W = W_{abs} + W_{ref} + W_{trans} \quad (4)$$

or, in normalized form,

$$\alpha + \rho + \tau = 1 \quad (5)$$

where

- α = absorptivity
- ρ = reflectivity
- τ = transmissivity

Absorption refers to the portion of incident infrared radiation that is absorbed by the material and converted into internal energy. Reflection is the portion of radiation that is redirected from the surface without being absorbed. Transmission is the fraction of radiation that passes through the material.

For an opaque body, such as metals and most engineering materials, transmission is negligible ($\tau \approx 0$). Therefore,

$$\alpha + \rho = 1 \quad (6)$$

According to Kirchhoff's law of thermal radiation, the absorptivity of a material is equal to its emissivity at thermal equilibrium,

$$\alpha = \varepsilon \quad (7)$$

Thus, for an opaque object,

$$\varepsilon + \rho = 1 \quad (8)$$

where ε is the emissivity of the object. A perfect blackbody absorbs all incident radiation and therefore has

$$\varepsilon = 1, \quad \rho = 0 \quad (9)$$

whereas a perfectly reflecting surface would have

$$\varepsilon = 0, \quad \rho = 1 \quad (10)$$

In practical thermography, most real objects behave neither as perfect blackbodies nor perfect reflectors. Their emissivity depends on material composition, surface roughness, oxidation, and wavelength. Materials with nearly constant emissivity over a spectral range are called *grey bodies*, while materials whose emissivity varies strongly with wavelength are known as *selective radiators*. For example, glass behaves almost like a blackbody at certain infrared wavelengths but is highly reflective or transmissive at others.

Understanding absorption, reflection, and transmission is essential in infrared thermography because the radiation detected by an infrared camera is not solely emitted by the target object. The measured signal may also contain reflected radiation from surrounding objects and radiation emitted by the atmosphere, which must be accounted for to obtain accurate temperature measurements.

3.4 Atmospheric Attenuation and Total Radiation Received by the Camera

Between the target object and the infrared camera lies the atmosphere, which affects the propagation of infrared radiation. Atmospheric gases such as water vapor, carbon dioxide, and ozone absorb and scatter a portion of the emitted radiation, thereby reducing the amount of energy reaching the detector. This phenomenon is known as *atmospheric attenuation*.

The attenuation strongly depends on wavelength. For this reason, infrared cameras are typically designed to operate within atmospheric transmission windows where absorption is minimal. The most important windows are:

- Mid-Wave Infrared (MWIR): $3 - 5 \mu m$
- Long-Wave Infrared (LWIR): $7.5 - 13.5 \mu m$

Within these wavelength ranges, infrared radiation can travel through the atmosphere with relatively low losses, making them suitable for thermal imaging applications.

In practical thermography, the radiation received by the camera is not solely the radiation emitted by the target object. Instead, the detector receives contributions from three different sources:

1. Radiation emitted by the target object.
2. Radiation from surrounding objects reflected by the target surface.
3. Radiation emitted by the atmosphere itself.

The contribution from the target object is given by

$$W_{obj} = \varepsilon \tau W_{object} \quad (11)$$

where ε is the emissivity of the object and τ is the atmospheric transmittance.

The reflected ambient radiation contribution is

$$W_{ref} = (1 - \varepsilon) \tau W_{amb} \quad (12)$$

where W_{amb} represents the radiation originating from the surrounding environment.

The atmosphere also emits thermal radiation according to Kirchhoff's law. Its contribution is

$$W_{atm} = (1 - \tau) W_{atm} \quad (13)$$

where $(1 - \tau)$ represents the effective emissivity of the atmosphere.

Therefore, the total radiation reaching the infrared camera detector can be expressed as

$$W_{tot} = \varepsilon\tau W_{object} + (1 - \varepsilon)\tau W_{amb} + (1 - \tau)W_{atm} \quad (14)$$

where

- ε : emissivity of the target object
- τ : atmospheric transmittance
- W_{object} : radiation emitted by the object
- W_{amb} : ambient reflected radiation
- W_{atm} : radiation emitted by the atmosphere

This equation forms the basis of quantitative infrared thermography. To accurately determine the temperature of an object, modern infrared cameras must compensate for emissivity variations, atmospheric attenuation, ambient reflections, and atmospheric emission. Failure to account for these factors can lead to significant errors in temperature measurement, particularly when observing low-emissivity objects or targets located at large distances.

3.5 *Electronic, Vibrational, and Rotational Transitions*

Matter interacts with electromagnetic radiation through quantized energy transfers. A photon is absorbed when its energy exactly matches the difference between two allowed states:

$$E = h\nu = \frac{hc}{\lambda} \quad (15)$$

where h is Planck's constant, ν is the frequency, c is the speed of light, and λ is the wavelength.

Depending on the energy of the incident radiation, three primary transitions occur:

Electronic Transitions (UV/Visible) Electrons are excited to higher energy levels ($h\nu = E_2 - E_1$). While not the main driver of thermal infrared absorption, these transitions strongly influence bulk optical properties and refractive indices.

Vibrational Transitions (Infrared) Atoms vibrate around their equilibrium positions in discrete modes (e.g., symmetric stretching, asymmetric stretching, and bending). This is the primary mechanism for infrared absorption, occurring when:

$$h\nu = E'_v - E_v \quad (16)$$

where E_v and E'_v are distinct vibrational states.

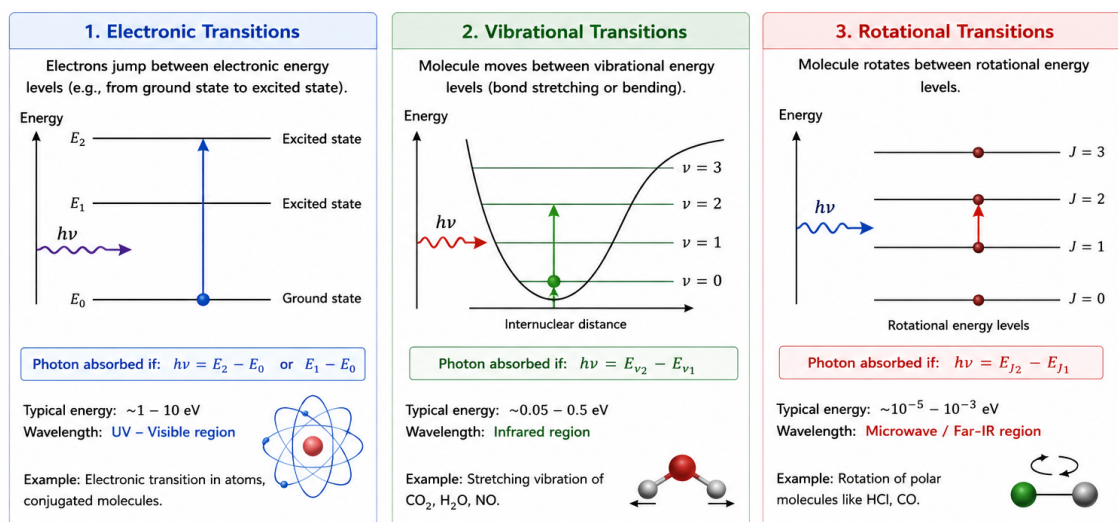


Figure 3 When the photon energy h matches the difference between two allowed energy levels $\rightarrow$ the photon is absorbed, and the molecule/atom transitions to a higher energy state.

Rotational Transitions (Microwave/Far-IR) Molecules rotate about their center of mass with quantized energy $E_J = BJ(J+1)$, where J is the rotational quantum number and B is the rotational constant. Transitions occur when:

$$h\nu = E_{J+1} - E_J \quad (17)$$

Rotational transitions frequently couple with vibrational transitions, yielding complex absorption spectra.

3.6 Dipole Moment and Infrared Absorption

For a molecule to absorb infrared radiation, matching the photon's energy is not enough; the molecular dipole moment ($\mu = qd$, where q is charge and d is distance) must also physically change during vibration.

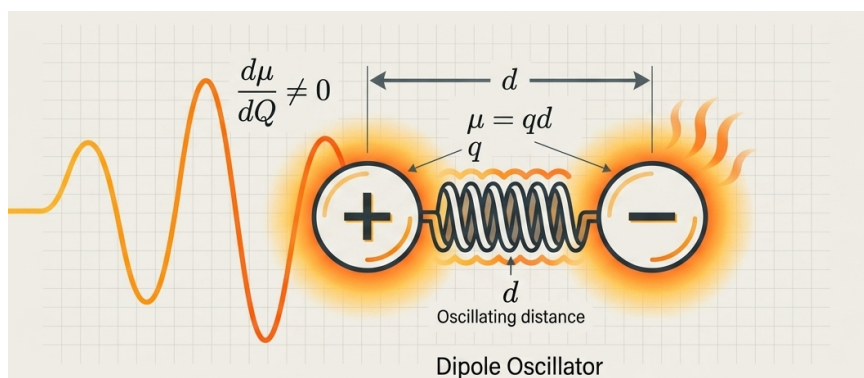


Figure 4 Molecules act as microscopic antennas catching infrared waves - To absorb an infrared wave, a molecule's vibration must physically change its dipole moment. If the charge distribution fluctuates, it creates an oscillating electric field that perfectly couples to the incoming radiation.

When an infrared wave's oscillating electric field interacts with a molecule, energy transfer only occurs if the dipole moment fluctuates along the vibrational coordinate (Q):

$$\frac{d\mu}{dQ} \neq 0 \quad (18)$$

If this condition is met, the electric field seamlessly couples to the molecule, transferring energy and causing absorption.

3.7 IR Inactive vs. IR Active Molecules

IR Inactive (N_2 , O_2) Homonuclear diatomic molecules possess a perfectly symmetric charge distribution. Their dipole moment remains perpetually zero ($\mu = 0$ and therefore $\frac{d\mu}{dQ} = 0$). Consequently, the IR wave cannot couple to their vibrations, rendering them virtually invisible to infrared radiation.

	IR Active Molecules (Absorbers)	IR Inactive Molecules (Transparent)
Geometry		
Dipole Moment		
Interaction with IR Field		

Figure 5 Nitrogen and oxygen make up 99 percent of the atmosphere but are physically invisible to infrared. Heat is only trapped by molecules like water vapor and carbon dioxide, whose asymmetric vibrations create the necessary dipole fluctuations to absorb passing photons.

IR Active (H_2O , CO_2 , CO) These molecules undergo charge distribution fluctuations during vibration, creating the oscillating electric fields needed to absorb passing photons.

- **Water (H_2O):** Its bent geometry provides a permanent dipole that strongly fluctuates during vibrational modes.
- **Carbon Dioxide (CO_2):** Despite being a perfectly linear molecule with no *permanent* dipole, specific vibrational modes (like bending) induce *temporary* dipoles, allowing it to efficiently trap targeted infrared wavelengths.

These dipole dynamics are the foundational mechanisms behind atmospheric heat retention, infrared transmission, and IR stealth technologies.

3.8 Atmospheric Transmission Windows

The Earth's atmosphere transmits infrared radiation selectively. Molecular absorption by H_2O , CO_2 , O_3 , and other trace gases creates broad absorption bands that divide the infrared spectrum into distinct transmission windows.

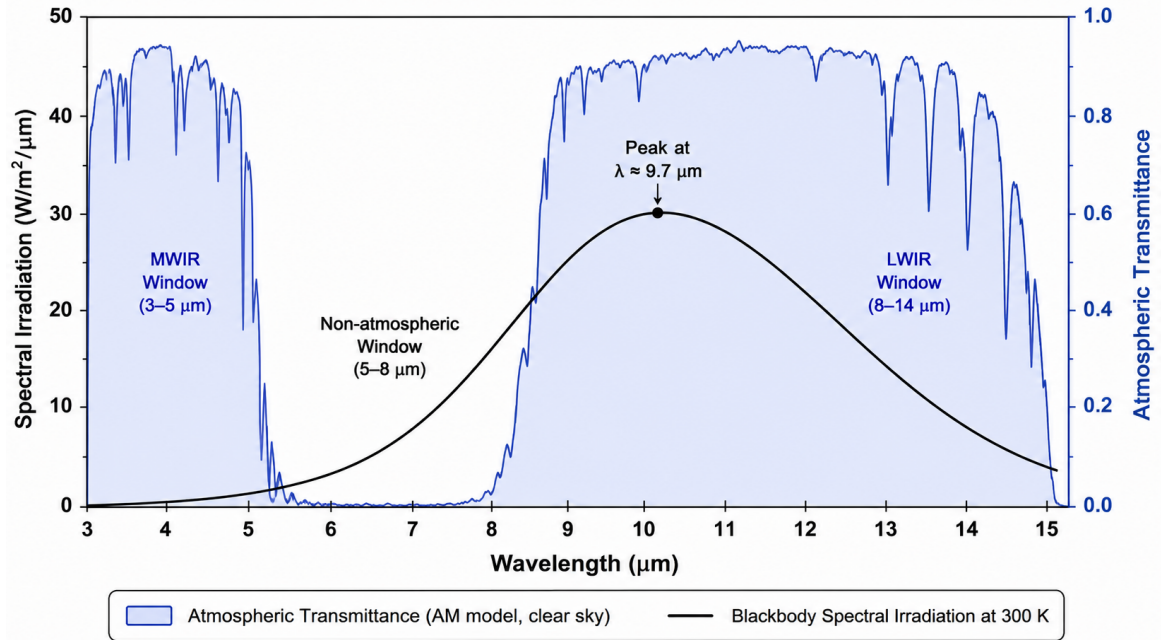


Figure 6 Atmospheric transmittance data from the HITRAN/MODTRAN database under clear-sky, sea-level conditions together with the spectral irradiation of a 300 K blackbody. The MWIR (3–5 μm), non-atmospheric (5–8 μm), and LWIR (8–14 μm) spectral regions relevant to infrared stealth and passive radiative cooling are indicated.

Two windows are of primary relevance to thermal imaging and IR stealth [21]:

- **MWIR window (3–5 μm):** Dominated by thermal contrast imaging of objects near ambient temperature ($\sim 300 \text{ K}$). Atmospheric transmittance in this band can exceed 90% under clear conditions.
- **LWIR window (8–14 μm):** The primary band for passive thermal imaging of room-temperature and elevated-temperature objects. The peak of the blackbody spectrum at 300 K falls near 9.7 μm , squarely within this window.

A spectrally selective stealth emitter must suppress thermal emission in *both* windows simultaneously to be effective against sensor systems that operate in either or both bands.

3.9 Radiative Cooling Window

Between the two atmospheric transmission windows lies the non-atmospheric window (5–8 μm), in which the atmosphere is largely opaque due to strong absorption by H_2O vibrational bands and CO_2 bending modes [22]. Thermal radiation emitted by a surface in this spectral band is absorbed by the atmosphere within a few tens of metres and does not

reach ground-based IR sensors. However, the absorbed atmospheric energy is re-emitted isotropically and contributes to the energy balance of the surrounding atmosphere rather than to the detected IR signature of the target.

Infrared transmittance ($\tau = \frac{I}{I_0}$) through the atmosphere is not uniform. Molecules absorb photons whose energy ($E = \frac{hc}{\lambda}$) exactly matches their allowed vibrational or rotational states, leaving clear regions of high transparency known as *atmospheric windows*.

Wavelength (μm)	Classification	Mechanism & Significance
2.7, 6.3, > 14	Absorption (H_2O)	Asymmetric structure and permanent dipole create strong attenuating bands.
4.3, 15	Absorption (CO_2)	Bending/stretching vibrations induce temporary dipoles, trapping heat.
3 – 5	MWIR Window	Minimal attenuation. Critical for missile tracking and long-range detection.
8 – 14	LWIR Window	High transmission region. The standard for commercial thermal imaging.

Table 2 Summary of primary atmospheric absorption bands and transmission windows.

The non-atmospheric window therefore provides a thermally and strategically ideal channel for heat dissipation: a surface engineered to radiate strongly at 5–8 μm can shed significant heat without increasing its IR detectability. Moreover, for high-altitude platforms where the atmospheric column is thin, the effective sky temperature can approach values well below ambient [19], enabling genuine sub-ambient radiative cooling.

3.10 The Physical Synergy of the LWIR Window

Atmospheric windows exist wherever molecular transition gaps occur. The LWIR window (8–14 μm) is particularly fortuitous because it perfectly overlaps with the peak thermal emission of objects at room temperature ($\sim 300\text{ K}$). According to Wien’s displacement law:

$$\lambda_{max} = \frac{2898}{300} \approx 9.7\ \mu\text{m} \quad (19)$$

Because 9.7 μm falls squarely within the transmission window, infrared photons from room-temperature targets can efficiently reach sensors without atmospheric interference. This precise overlap forms the basis of modern thermal imaging and infrared stealth research.

3.11 Working Principle of the Multilayer Thin-Film Emitter

The proposed Ge/MgF₂/SiO₂ structure achieves the desired spectral response through two concurrent physical mechanisms operating in different spectral regions, as illustrated conceptually in Fig. 1.

Photonic bandgap reflectance (3–5 μm and 8–14 μm): The alternating Ge and MgF₂

layers form a 1D photonic crystal whose reflectance bandgap is engineered to cover the MWIR and LWIR atmospheric windows. When a plane wave at a wavelength within the bandgap is incident on the structure, destructive interference of multiply-reflected waves within the multilayer produces near-unity reflectance. By Kirchhoff's law (2), high reflectance corresponds directly to low absorptance and hence low emissivity. The position of the bandgap centre wavelength is controlled by:

$$\lambda_c = 2(n_H d_H + n_L d_L) \quad (20)$$

and the bandgap width scales with $\Delta n/\bar{n}$, where $\bar{n}$ is the average refractive index [6].

Phonon-polariton absorption (5–8 μm): In the non-atmospheric window, the photonic bandgap does not provide suppression, and incident radiation penetrates through the Ge/MgF₂ multilayer into the SiO₂ substrate. SiO₂ in the cristobalite or amorphous phase exhibits a strong phonon resonance associated with the asymmetric Si–O–Si stretching mode, producing a large imaginary part of the refractive index ($k_{\text{SiO}_2} > 1$) between approximately 7 and 9 μm [14]. This resonance causes strong absorption of the transmitted radiation within the substrate, and by Kirchhoff's law, correspondingly strong thermal emission in the same band. The SiO₂ substrate therefore functions as a *phonon-polariton* selective emitter whose emission band overlaps precisely with the radiative cooling window.

4. Infrared Camera: Components and Working Principle

An infrared camera consists of three major components: infrared optics, infrared detectors, and signal processing electronics. The optics collect and focus the incoming infrared radiation onto the detector array, where it is converted into electrical signals. These signals are then processed to generate a thermal image.

4.1 Infrared Optics

Unlike visible-light cameras, infrared cameras cannot use ordinary glass lenses because glass strongly absorbs infrared radiation. Therefore, special materials that are transparent to infrared wavelengths are used.

For MWIR (3 – 5 μm) systems, silicon (Si) lenses are commonly employed, while LWIR (8 – 14 μm) systems generally use germanium (Ge) lenses. These lenses are usually coated with anti-reflective layers to maximize transmission and reduce optical losses.

Infrared optics collect the thermal radiation emitted by the target and focus it onto the detector focal plane array (FPA). The quality of the lens directly affects the spatial resolution, sensitivity, and imaging performance of the camera.

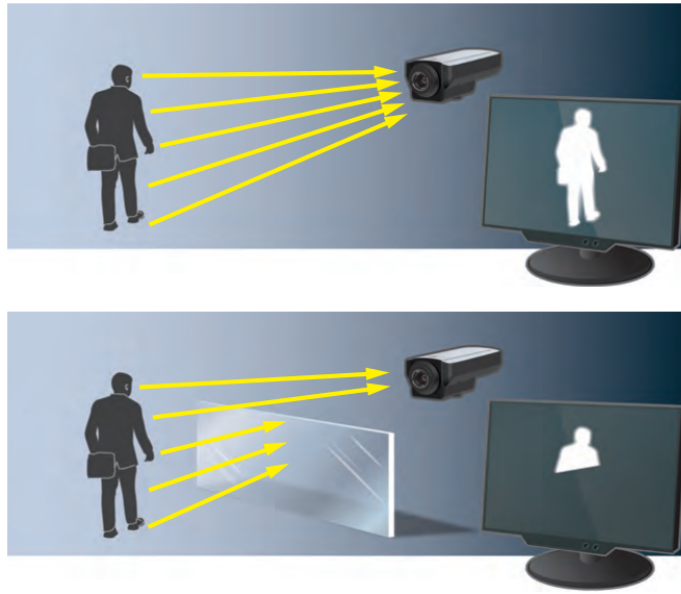


Figure 7 Glass preventing thermal imaging

4.2 Infrared Detectors

The detector is the most important component of an infrared camera. It converts incident infrared radiation into an electrical signal that can be processed and displayed as an image. Infrared detectors are broadly classified into two categories:

1. Thermal Detectors (Non-Quantum Detectors)
2. Quantum Detectors (Photon Detectors)

4.2.1 Thermal Detectors

Thermal detectors operate by absorbing infrared radiation and converting it into heat. The resulting temperature rise produces a measurable change in a physical property of the detector material, such as electrical resistance.

The most widely used thermal detector is the microbolometer. A microbolometer pixel absorbs incident infrared radiation, causing its temperature to increase slightly. This temperature change modifies the electrical resistance of the sensing material, which is measured by the readout electronics.

The operation can be summarized as:

IR Radiation → Temperature Increase → Resistance Change → Electrical Signal (21)

Thermal detectors offer several advantages:

- Operate at or near room temperature.
- Broad spectral response.

- Compact and low-cost construction.

However, they generally have lower sensitivity and slower response times compared to quantum detectors.

4.2.2 Quantum Detectors

Quantum detectors operate on the principle of photon absorption in semiconductor materials. When an infrared photon with sufficient energy strikes the detector, it excites an electron from the valence band to the conduction band, generating electron-hole pairs.

The generated charge carriers produce a measurable current or voltage proportional to the incident infrared radiation.

$$h\nu \geq E_g \quad (22)$$

where $h\nu$ is the photon energy and E_g is the semiconductor band-gap energy.

Since MWIR photons possess higher energy than LWIR photons, MWIR detectors generally exhibit higher sensitivity and faster response. Quantum detectors provide excellent detectivity and high-speed operation but require cooling to suppress thermal noise.

Common quantum detector materials include:

- InSb (Indium Antimonide)
- HgCdTe (Mercury Cadmium Telluride)
- Quantum Well Infrared Photodetectors (QWIPs)

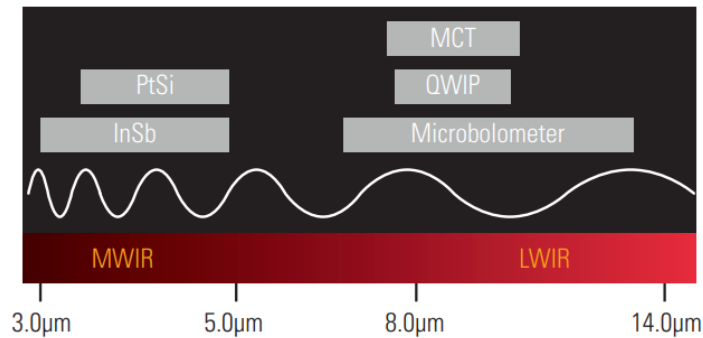


Figure 8 Examples of detector materials and their spectral responses relative to IR midwave (MW) and longwave (LW) bands

4.3 Cooling Techniques

Quantum detectors generate significant thermal noise at room temperature. Therefore, cooling is often necessary to improve detector sensitivity and signal-to-noise ratio.

Three commonly used cooling techniques are described below.

4.3.1 Thermoelectric (Peltier) Cooling

Thermoelectric cooling uses the Peltier effect to transfer heat from one side of a semiconductor junction to the other when an electric current flows through it.

The detector is mounted on the cold side of the thermoelectric cooler, while the generated heat is dissipated through the hot side. Peltier coolers are compact, reliable, and suitable for moderate cooling requirements.

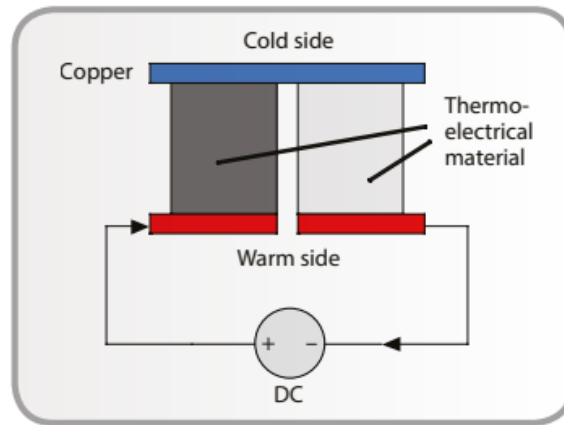


Figure 9 Single stage Peltier cooler

4.3.2 Stirling Cycle Cooling

Stirling coolers are mechanical cryogenic coolers widely used in high-performance infrared systems. They operate by cyclic compression and expansion of a working gas, which removes heat from the detector assembly.

Stirling coolers provide significantly lower operating temperatures than thermoelectric coolers and are commonly used with MWIR and LWIR quantum detectors.

4.3.3 Liquid Nitrogen Cooling

Liquid nitrogen cooling is one of the earliest methods used for infrared detectors. In this technique, the detector is mounted inside a Dewar flask containing liquid nitrogen at approximately 77 K.

The extremely low temperature greatly reduces thermal noise and improves detector sensitivity. Although highly effective, liquid nitrogen cooling is bulky and requires periodic refilling, making it less suitable for portable systems.

4.4 Working of a Microbolometer Infrared Camera

Microbolometers are the most commonly used detectors in uncooled infrared cameras. They belong to the class of thermal detectors and operate by converting incident infrared

radiation into heat. The resulting temperature change produces a variation in electrical resistance, which is measured and processed to generate a thermal image.

A microbolometer pixel consists of an infrared absorber, a temperature-sensitive resistive material, supporting legs, and a readout integrated circuit (ROIC). The sensing element is typically fabricated from vanadium oxide (VO_x) or amorphous silicon (a-Si) and is suspended above the substrate by thin support structures. This configuration provides excellent thermal isolation from the surroundings.

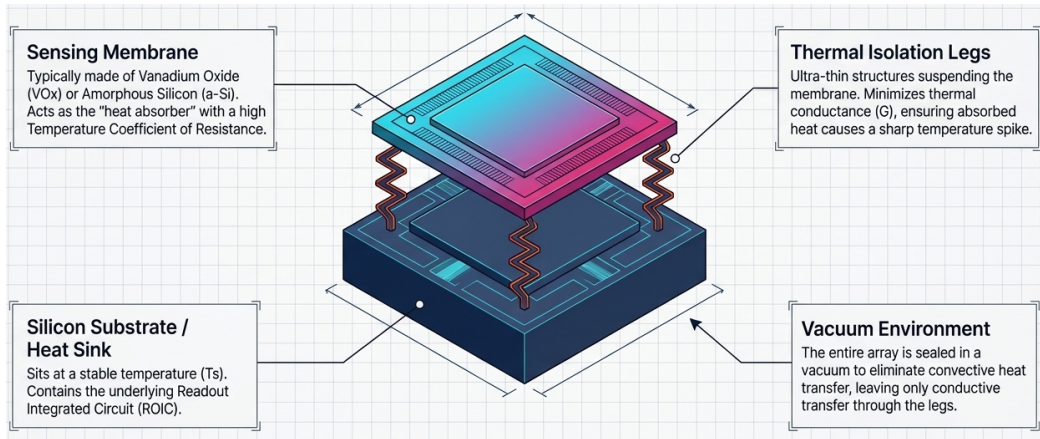
When infrared radiation emitted by an object reaches the detector, it is absorbed by the microbolometer membrane, causing a slight increase in temperature. The temperature rise changes the electrical resistance of the sensing material according to

$$\Delta R = \alpha R_0 \Delta T \quad (23)$$

where

- R_0 is the initial resistance,
- ΔT is the temperature increase,
- α is the temperature coefficient of resistance (TCR).

The ROIC continuously measures these resistance variations and converts them into voltage signals. The signals from all pixels are then digitized and processed to form a two-dimensional thermal image.



Since the detector responds to temperature changes rather than individual photons, microbolometers can operate near room temperature without requiring cryogenic cooling. This significantly reduces system complexity, size, power consumption, and cost.

Modern microbolometer focal plane arrays (FPAs) typically contain hundreds of thousands of pixels, with resolutions ranging from 160×120 pixels to 1024×1024 pixels or higher. The temperature information from each pixel is combined to produce a detailed thermal map of the observed scene.

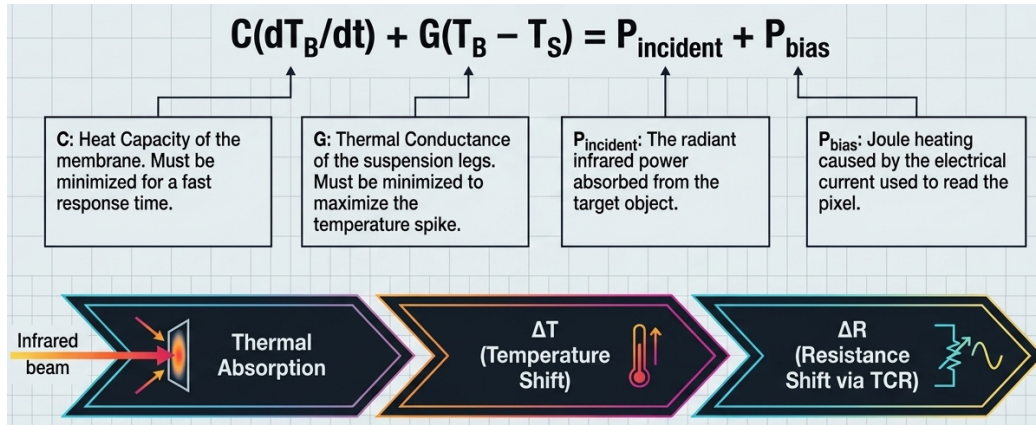


Figure 10 Working of a Microbolometer

The major advantages of microbolometers include compact size, low power consumption, broad spectral response, and room-temperature operation. However, they generally exhibit lower sensitivity and slower response times compared to cooled quantum detectors.

4.5 Image Processing and Thermal Image Formation

The electrical signals generated by the infrared detector do not directly form a usable thermal image. Before the image can be displayed, the signals must undergo several stages of processing to improve accuracy, remove noise, and enhance image quality. This sequence of operations is known as image processing and thermal image formation.

After infrared radiation is focused onto the detector array, each pixel converts the incident radiation into an electrical signal proportional to the received thermal energy. These analog signals are first collected by the Readout Integrated Circuit (ROIC), which amplifies and multiplexes the outputs from all detector elements.

The analog signals are then converted into digital values using an Analog-to-Digital Converter (ADC). The resulting digital data represent the intensity of infrared radiation detected by each pixel of the focal plane array.

However, due to manufacturing variations, individual detector pixels do not respond identically to the same amount of radiation. This produces fixed-pattern noise and non-uniform image brightness. To overcome this problem, a process known as Non-Uniformity Correction (NUC) is applied. NUC compensates for pixel-to-pixel variations and ensures a uniform response across the detector array.

In addition to non-uniformity correction, dead-pixel correction algorithms are employed to identify defective detector elements and replace their values using information from neighboring pixels. Noise reduction techniques are also applied to suppress random fluctuations arising from detector noise and electronic circuitry.

Once the image has been corrected, contrast enhancement algorithms are used to improve visibility. Since the temperature range of a scene may be much larger than the display range, histogram stretching and dynamic range compression techniques are often employed to

highlight small temperature differences.

The processed image is then mapped to a grayscale or false-color palette. In grayscale imaging, hotter regions appear brighter than cooler regions. In false-color imaging, different colors are assigned to different temperature ranges, making thermal variations easier to interpret. Common palettes include Ironbow, Rainbow, Arctic, and White-Hot.

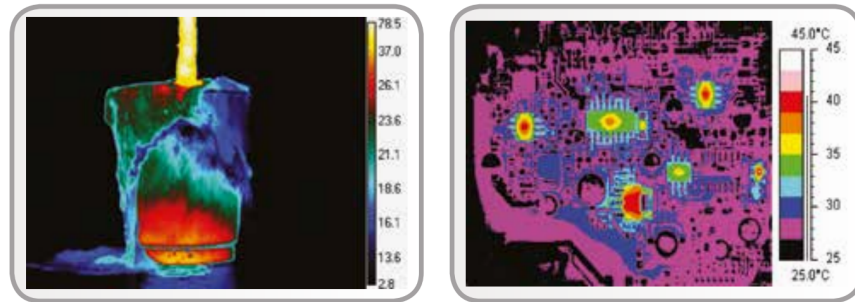


Figure 11 (a)Rainbow scale showing lower temperatures towards the blue end of the spectrum
(b)Isotherm color scale with each color having an isotherm width of 2°C

The complete thermal image formation process can be represented as

IR Radiation → Detector Array → ROIC → ADC → Image Corrections

→ Contrast Enhancement → Color Mapping → Thermal Image(24)

Modern infrared cameras further incorporate advanced image-processing techniques such as object detection, target tracking, image fusion, and artificial intelligence-based analysis. These techniques improve image interpretation and enable automatic identification of thermal anomalies in industrial, medical, and defense applications.

Thus, image processing serves as the final stage in the infrared imaging chain, transforming raw detector signals into accurate and visually meaningful thermal images that can be analyzed by the user.

4.6 Applications of Infrared Cameras

Infrared cameras are used in many areas because they provide non-contact thermal information. In industry, they are used for predictive maintenance, inspection of electrical systems, detection of hot spots, and monitoring of manufacturing processes. In medicine, infrared thermography helps in fever screening and in observing temperature variations related to inflammation and blood circulation.

In defense and surveillance, infrared cameras are used for night vision, border monitoring, target detection, missile guidance, and infrared stealth analysis. In science, they are used in astronomy, environmental monitoring, and thermal research. In autonomous systems, infrared cameras help in object detection and navigation under poor lighting conditions.

The wide range of applications shows that infrared imaging is not only a visual technology, but also a powerful tool for measuring and understanding thermal behavior.

4.7 Implications for Infrared Stealth

The understanding of infrared radiation, atmospheric transmission windows, and the interaction of electromagnetic waves with materials forms the foundation of infrared stealth technology. Since modern thermal imagers primarily operate in the MWIR ($3\text{--}5\ \mu\text{m}$) and LWIR ($8\text{--}14\ \mu\text{m}$) atmospheric windows, reducing the emitted radiation within these wavelength bands can significantly decrease the probability of detection. Infrared stealth can be achieved through several approaches, including the use of low-emissivity coatings, multilayer optical films, photonic crystals, metamaterials, and thermal insulation structures. These materials are engineered to suppress thermal emission in the atmospheric windows while maintaining efficient heat dissipation at non-atmospheric wavelengths. Recent studies have demonstrated that multilayer Ge/Ag optical films can achieve very low emissivities in both the MWIR and LWIR bands while exhibiting higher emissivity in the $5\text{--}8\ \mu\text{m}$ region for thermal management, thereby satisfying the dual requirements of infrared camouflage and heat dissipation. Such wavelength-selective control of emissivity represents one of the most promising directions in modern infrared stealth technology.

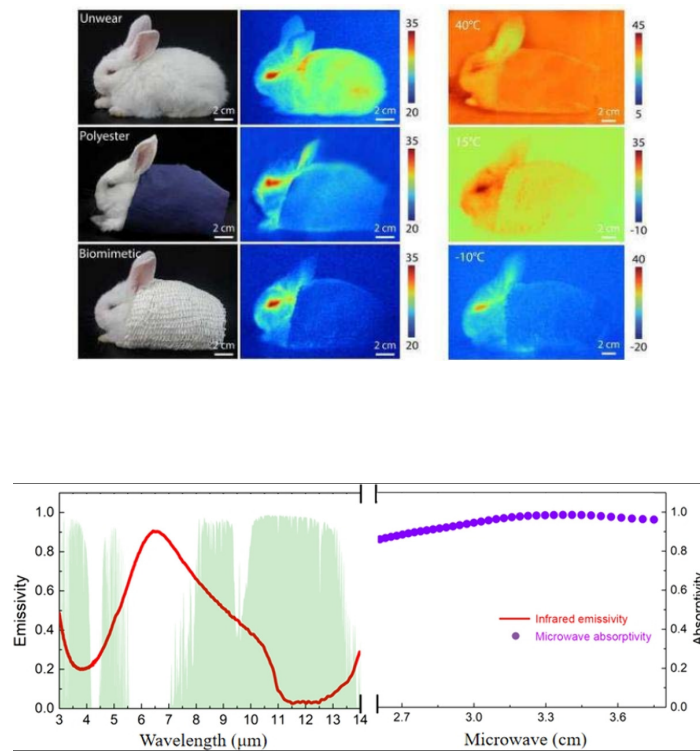


Figure 12 (a)Infrared stealth effect of different fabrics (b)Ideal spectral emissivity profile for infrared stealth materials. Low emissivity is maintained within the atmospheric transmission windows ($3\text{--}5\ \mu\text{m}$ and $8\text{--}14\ \mu\text{m}$) to suppress infrared signatures, while high emissivity in the $5\text{--}8\ \mu\text{m}$ non-atmospheric window enhances radiative cooling and thermal management.

5. Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is a powerful experimental technique used to study the interaction of infrared radiation with matter. It is widely employed for determining the optical properties of materials, including reflectance, transmittance, absorptance, and emissivity.

In infrared stealth research, FTIR spectroscopy serves as the primary characterization tool for evaluating the spectral emissivity of fabricated materials and multilayer structures.

5.1 Introduction to FTIR

Unlike conventional dispersive spectrometers that measure one wavelength at a time, FTIR spectroscopy simultaneously collects information from all wavelengths. This approach significantly improves measurement speed, spectral resolution, and signal-to-noise ratio.

The technique is based on the generation of an interferogram using a Michelson interferometer followed by mathematical Fourier transformation.

5.2 Working Principle of FTIR

The operation of FTIR can be divided into three major stages:

1. Generation of an interferogram.
2. Interaction of infrared radiation with the sample.
3. Fourier transformation of the detected signal.

Broadband infrared radiation emitted from the source enters a Michelson interferometer where it is split into two beams. These beams travel different optical paths and recombine to produce an interference pattern known as the interferogram.

The interferogram contains information from all wavelengths simultaneously. After interacting with the sample, the resulting signal is recorded by the detector and transformed into a spectrum using Fourier analysis.

5.3 Michelson Interferometer

The Michelson interferometer is the core component of an FTIR spectrometer. It consists of:

- Infrared source
- Beam splitter
- Fixed mirror
- Moving mirror

- Detector

The beam splitter divides the incident infrared radiation into two equal components. One beam travels toward a fixed mirror while the other travels toward a moving mirror.

After reflection, the beams recombine at the beam splitter. Because the moving mirror continuously changes the optical path length, constructive and destructive interference occur, producing a varying intensity pattern.

The optical path difference is given by

$$\delta = 2d \quad (25)$$

where d is the displacement of the moving mirror.

5.4 Formation of the Interferogram

The detector records the intensity variation as a function of optical path difference. This recorded signal is known as the interferogram.

Mathematically, the interferogram may be expressed as

$$I(\delta) = \int_0^\infty S(\tilde{\nu}) \cos(2\pi\tilde{\nu}\delta) d\tilde{\nu} \quad (26)$$

where $S(\tilde{\nu})$ is the spectral intensity distribution and $\tilde{\nu}$ is the wavenumber.

The interferogram contains the complete spectral information of the source.

5.5 Fourier Transformation

The recorded interferogram is not directly useful because it is expressed as a function of optical path difference rather than wavelength.

A Fourier transform is therefore applied to recover the spectral intensity distribution:

$$S(\tilde{\nu}) = \mathcal{F} \{I(\delta)\} \quad (27)$$

where $\mathcal{F}$ denotes the Fourier transform operator.

The resulting spectrum provides information about the interaction between the sample and infrared radiation.

5.6 Measurement of Reflectance

For infrared stealth materials, the most important quantity measured by FTIR is the spectral reflectance.

A reference mirror with nearly unity reflectance is first measured to obtain the reference intensity I_{ref} . The sample is then measured to obtain I_{sample} .

The reflectance is calculated as

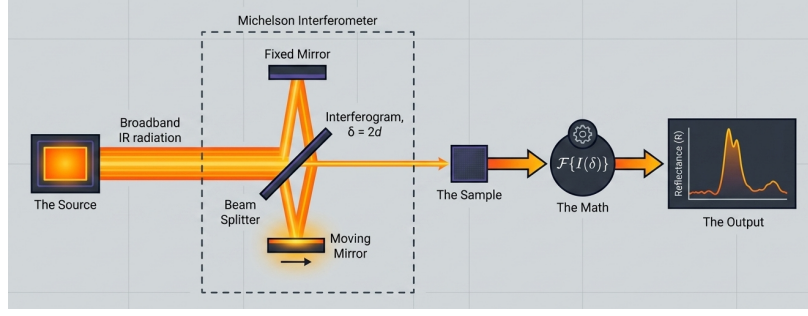


Figure 13 FTIR spectroscopy is the absolute standard for verifying stealth materials. By splitting a beam and altering its optical path length, we capture data across all wavelengths simultaneously.

Because our material is opaque (T0), we calculate emissivity directly via Kirchhoff's law:

$$\text{Epsilon}(\lambda) = 1 - R(\lambda).$$

$$R(\lambda) = \frac{I_{\text{sample}}(\lambda)}{I_{\text{ref}}(\lambda)} \quad (28)$$

This procedure eliminates instrumental variations and provides the true spectral reflectance of the material.

5.7 Determination of Spectral Emissivity

Once the reflectance spectrum has been obtained, the emissivity spectrum can be determined using Kirchhoff's law.

For a general material,

$$A(\lambda) + R(\lambda) + T(\lambda) = 1 \quad (29)$$

and

$$\varepsilon(\lambda) = A(\lambda) \quad (30)$$

Therefore,

$$\varepsilon(\lambda) = 1 - R(\lambda) - T(\lambda) \quad (31)$$

For opaque multilayer structures,

$$T(\lambda) \approx 0 \quad (32)$$

which simplifies the expression to

$$\boxed{\varepsilon(\lambda) = 1 - R(\lambda)} \quad (33)$$

This equation is extensively used in infrared stealth research because most multilayer emitters and camouflage coatings are opaque in the infrared region.

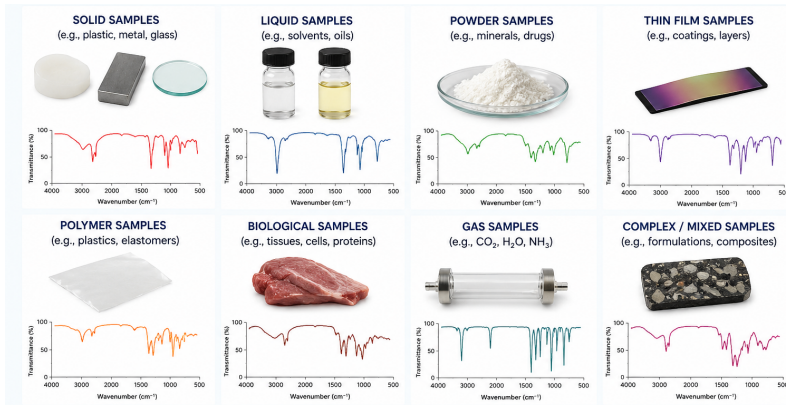


Figure 14 Applicability of FTIR spectroscopy to various sample forms including solids, liquids, powders, thin films, polymers, biological samples, gases, and composite materials.

5.8 Importance of FTIR in Infrared Stealth Research

FTIR spectroscopy provides a direct method for verifying the spectral emissivity profile of a fabricated material. By comparing the experimentally measured emissivity spectrum with the designed spectrum, researchers can evaluate whether the material exhibits:

- Low emissivity in the MWIR atmospheric window,
- High emissivity in the non-atmospheric region,
- Low emissivity in the LWIR atmospheric window.

Therefore, FTIR acts as a crucial bridge between theoretical optical design, numerical simulation, and experimental validation of infrared stealth materials.

6. Selection of Materials for Infrared Stealth Emitters

The performance of an infrared stealth emitter depends strongly on the choice of materials used in its multilayer structure. Since the target is to reduce detectability in the atmospheric infrared windows, the selected materials must satisfy both optical and practical design requirements. In particular, the material system should provide low emissivity in the $3\text{--}5\ \mu\text{m}$ and $8\text{--}14\ \mu\text{m}$ atmospheric windows, while maintaining high emissivity in the $5\text{--}8\ \mu\text{m}$ non-atmospheric window for thermal radiation management.

6.1 Criteria for Material Selection: An Optophysical Approach

To successfully engineer an infrared stealth emitter, the material selection cannot be arbitrary; it must satisfy stringent optical, thermodynamic, and mechanical boundary conditions. We can categorize these criteria as follows:

1. The Optical and Dielectric Boundary Conditions

Complex Refractive Index Optimization: The material's optical response is governed by its complex refractive index, $\tilde{n} = n + i\kappa$. The real part (n) must support phase manipulation, while the imaginary extinction coefficient (κ) must be tailored to either suppress or enhance thermal emission in specific infrared bands.

Maximum Refractive-Index Contrast: Adjacent layers must exhibit a massive divergence in their real refractive indices ($\Delta n = |n_H - n_L|$). According to the Fresnel equations, the reflection coefficient at an interface at normal incidence is governed by:

$$R = \left| \frac{n_H - n_L}{n_H + n_L} \right|^2 \quad (34)$$

Maximizing this contrast enables highly efficient optical filtering, achieving the required interference patterns with fewer total layers.

Selective Extinction: Layers acting purely as reflective photonic filters must approach zero optical loss ($\kappa \rightarrow 0$), preserving wave amplitude. Conversely, the primary emitting layer must leverage molecular vibrations or phonon resonances to maximize κ precisely at the target wavelengths to efficiently dissipate heat.

2. The Thermodynamic and Engineering Constraints

Thermal and Chemical Inertia: The coating must resist oxidation and thermal degradation when exposed to extreme environmental gradients or continuous operational heating.

Scalable Thin-Film Deposition: The materials must be compatible with standard high-throughput vacuum techniques (e.g., physical vapor deposition, sputtering) to transition from theoretical models to macroscopic, large-area coatings.

Mechanical Cohesion: The multilayer stack must mitigate thermal expansion mismatches to prevent delamination, micro-cracking, and peeling under mechanical or thermal stress.

6.2 The Physics of Multilayer Films: 1D Photonic Crystals

While complex 2D and 3D metasurfaces exist, one-dimensional multilayer dielectric films remain the absolute standard in stealth architecture due to their potent combination of fabrication scalability and mathematically precise wave manipulation.

By alternating high (n_H) and low (n_L) index materials, the stack operates as a **1D Photonic Crystal** (often acting as a Bragg reflector). The optical behavior of the entire

structure is dictated by the phase thickness of each individual layer:

$$\delta_j = \frac{2\pi}{\lambda} n_j d_j \cos \theta_j \quad (35)$$

where d_j is the physical thickness of the j -th layer and θ_j is the angle of wave propagation inside that medium.

By computationally optimizing the physical thickness (d) of each discrete layer, we can engineer specific phase shifts. This allows us to force destructive interference for wavelengths in the atmospheric transmission windows (achieving stealth) and constructive interference for outgoing thermal radiation in non-detectable bands (facilitating radiative cooling). Multilayers thus provide a deterministic, mathematically solvable pathway to infrared camouflage that is highly compatible with industrial manufacturing.

7. Theoretical Background and Simulation Methodology

To ensure the engineered stealth emitter functions beyond mere theoretical speculation, its optical response is subjected to a dual-paradigm validation. First, the **Transfer Matrix Method (TMM)** provides a rigorous, semi-analytical 1D framework for rapid thickness optimization. Second, **Finite Element Method (FEM)** simulations via COMSOL Multiphysics validate the 3D full-wave electromagnetic interactions, confirming power loss densities and physical vector field behaviors.

7.1 The 1D Analytical Paradigm: Derivation of the Transfer Matrix

The Transfer Matrix Method computes how electromagnetic waves propagate through a stratified medium by enforcing boundary conditions at every continuous interface.

Consider a plane wave propagating strictly along the z -axis through a multilayer stack. Inside the i -th layer (with complex refractive index $\tilde{n}_i$), the total electric (E) and magnetic (H) fields are a superposition of forward (+) and backward (−) traveling waves:

$$E_i(z) = E_i^+ e^{-ik_{zi}z} + E_i^- e^{ik_{zi}z} \quad (36)$$

$$H_i(z) = q_i (E_i^+ e^{-ik_{zi}z} - E_i^- e^{ik_{zi}z}) \quad (37)$$

where q_i is the optical admittance of the layer.

By evaluating these fields at the entrance ($z = 0$) and exit ($z = d_i$) of the layer, we mathematically link the boundaries. The phase accumulated across the layer is $\delta_i = \frac{2\pi\tilde{n}_i d_i}{\lambda}$. Eliminating the wave amplitudes yields the characteristic transfer matrix M_i for a single layer:

$$\begin{bmatrix} E(0) \\ H(0) \end{bmatrix} = \begin{bmatrix} \cos \delta_i & \frac{j}{q_i} \sin \delta_i \\ j q_i \sin \delta_i & \cos \delta_i \end{bmatrix} \begin{bmatrix} E(d_i) \\ H(d_i) \end{bmatrix} = M_i \begin{bmatrix} E(d_i) \\ H(d_i) \end{bmatrix} \quad (38)$$

Because the tangential components of E and H must be continuous across any interface,

the entire multilayer structure is simply the ordered product of its individual matrices:

$$M_{total} = \prod_{i=1}^N M_i = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (39)$$

From this global matrix M_{total} , the macroscopic reflection amplitude (r) is explicitly derived, allowing the immediate calculation of spectral Reflectance ($R = |r|^2$) across millions of algorithmic thickness permutations.

7.2 The 3D Numerical Paradigm: Derivation of the FEM Wave Equation

While TMM is exceptionally fast for 1D algorithmic sweeps, COMSOL Multiphysics is deployed to solve the fundamental 3D vector fields, accounting for physical geometry, absorption resonances, and transverse effects.

The derivation begins with Maxwell's curl equations in the frequency domain (assuming time-harmonic fields $e^{j\omega t}$):

$$\nabla \times \mathbf{E} = -j\omega\mu_0\mu_r\mathbf{H} \quad (40)$$

$$\nabla \times \mathbf{H} = j\omega\tilde{\epsilon}\mathbf{E} \quad (41)$$

where $\tilde{\epsilon} = \epsilon' - j\epsilon''$ is the complex permittivity, capturing both dielectric dispersion and optical absorption.

Taking the curl of the electric field equation and substituting the magnetic field equation yields the fundamental **Vector Wave Equation** solved by the COMSOL mesh:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \mathbf{E} \right) - k_0^2 \tilde{\epsilon}_r \mathbf{E} = 0 \quad (42)$$

By applying Floquet periodic boundary conditions laterally and defining input ports longitudinally, COMSOL computes the exact spatial distribution of $\mathbf{E}$. The physical absorption of the wave—driven largely by the phonon resonances in the SiO_2 layer—is extracted via the time-averaged power loss density (Q):

$$Q = \frac{1}{2} \text{Re}(\mathbf{J} \cdot \mathbf{E}^*) = \frac{1}{2} \omega \epsilon'' |\mathbf{E}|^2 \quad (43)$$

A higher Q directly indicates stronger local absorption and, consequently, higher thermal emissivity in that specific spatial region.

7.3 Mathematical Synthesis and Emissivity Extraction

Both computational paradigms must mathematically converge on the same thermodynamic conclusion. Whether summing incident and reflected port powers in COMSOL ($R = P_r/P_i$) or deriving it from M_{total} in TMM, we arrive at the spectral Transmittance (T)

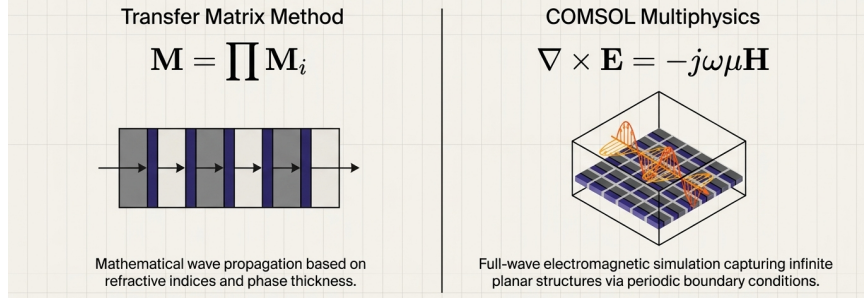


Figure 15 Dual validation: To ensure the emitter’s performance isn’t a theoretical artifact, the optical response is verified using two distinct paradigms: 1D transfer matrix calculations for rapid thickness optimization, and 3D finite-element Maxwell simulations to confirm physical field behaviors.

and Reflectance (R).

According to the conservation of electromagnetic energy:

$$A(\lambda) + R(\lambda) + T(\lambda) = 1 \quad (44)$$

Because the stealth emitter utilizes a highly attenuating SiO_2 substrate backed by structural materials, the incident infrared wave is completely extinguished before transmission ($T(\lambda) \approx 0$). Applying Kirchhoff’s law of thermal radiation ($\varepsilon = A$), both workflows distill down to the identical design imperative:

$$\boxed{\varepsilon(\lambda) \approx 1 - R(\lambda)} \quad (45)$$

This continuous mathematical workflow—from microscopic phase shifts (δ_i) to 3D tensor fields ($\mathbf{E}$), and ultimately to $\varepsilon(\lambda)$ —proves that by algorithmically sweeping the layer thicknesses (d_i), we can perfectly engineer and validate the macro-thermal signature of the stealth coating.

8. Design Methodology and Numerical Framework

8.1 Structural Configuration

The emitter consists of eight alternating thin-film layers of MgF_2 and Ge deposited on a $25\text{ }\mu\text{mSiO}_2$ substrate, with an air superstrate on the incident side. The layers are ordered from the top (air–film interface) to the bottom (film–substrate interface) as shown in Table 3. The alternating MgF_2/Ge sequence follows the low-index/high-index pattern that maximises the photonic bandgap reflectance for normally incident radiation [6].

8.2 Material Selection and Optical Dispersion Models

The three materials were selected based on their optical transparency, refractive index, and availability for thin-film deposition.

Germanium (Ge): Ge is transparent from 2 to $14\text{ }\mu\text{m}$ with a nearly dispersion-free

refractive index of $n = 4.003$ across this range [15]. Its high refractive index provides the largest available index contrast against common mid-IR dielectrics. The imaginary part of the refractive index (extinction coefficient) $k_{\text{Ge}} \approx 0$ in the 3–14 μm range for stoichiometric, undoped germanium [15]. In the simulations, Ge is assigned constant real and imaginary refractive indices of $n = 4.003$ and $k = 0$.

Magnesium fluoride (MgF_2): MgF_2 is transparent from 0.13 to approximately 8 μm with a slowly varying refractive index of $n \approx 1.350$ in the 3–8 μm range, falling to $n \approx 1.30$ near 8 μm [16]. Its chemical stability, low absorption, and compatibility with electron-beam evaporation make it a standard material for IR coatings. In the simulations, MgF_2 is assigned $n = 1.350$ and $k = 0$ as a constant approximation valid for wavelengths below 8 μm . The approximation introduces negligible error because MgF_2 layers occupy the high-reflectance region of the spectrum where transmittance through the structure is already near zero.

Silicon dioxide SiO_2 (amorphous): Amorphous SiO_2 possesses a strong phonon resonance near 8–9 μm arising from asymmetric Si–O–Si stretching, which produces a large extinction coefficient reaching $k > 4$ near 8.5 μm [14]. This resonance is the physical origin of the selective 5–8 μm emission in the proposed structure. The wavelength-dependent complex refractive index $\tilde{n}(\lambda) = n(\lambda) - ik(\lambda)$ of SiO_2 was implemented in COMSOL

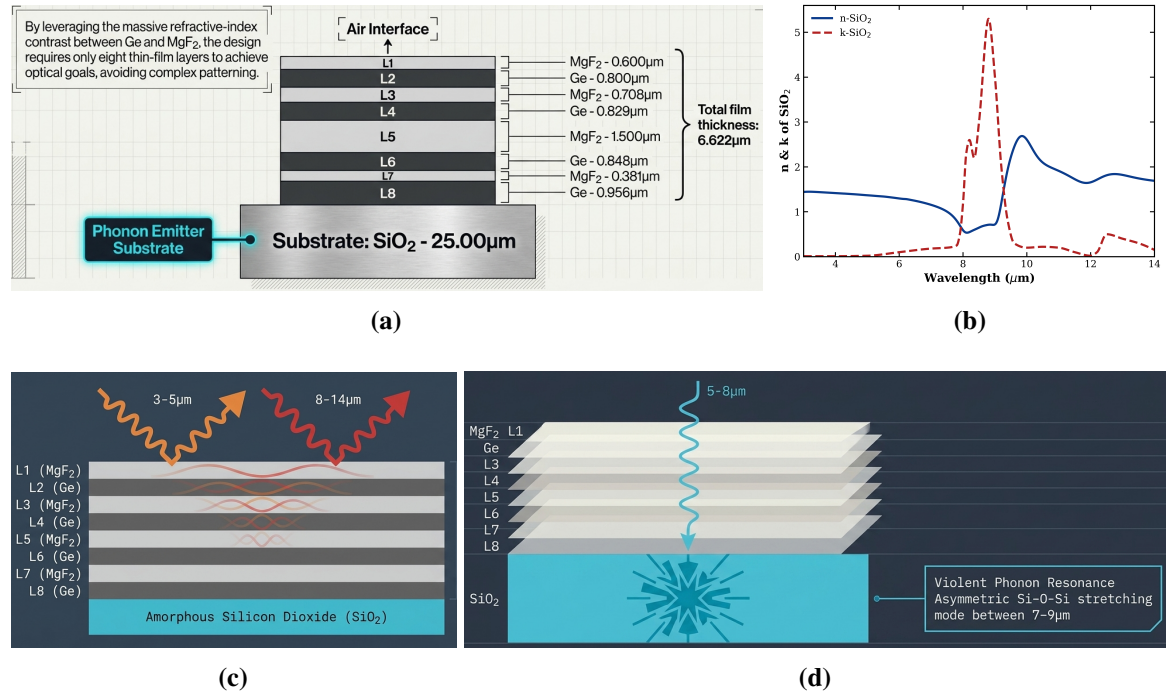


Figure 16 (a) Optimized multilayer thin-film architecture showing the layer sequence and corresponding thicknesses deposited on an SiO_2 substrate. (b) Refractive index (n) and extinction coefficient (k) of SiO_2 employed in the electromagnetic simulations. (c) Schematic illustration of the distributed Bragg reflection mechanism, where multiple reflections within the alternating Ge/ MgF_2 layers suppress thermal emission in the MWIR (3–5 μm) and LWIR (8–14 μm) atmospheric windows. (d) Illustration of the radiative cooling mechanism, in which the transparent multilayer stack enables strong phonon-polariton resonance within the SiO_2 substrate, enhancing thermal emission in the 5–8 μm non-atmospheric window.

as an interpolation function using the tabulated optical constants reported by Šimon and McMahon [14]. The interpolation functions were evaluated automatically at each simulation wavelength.

8.3 Governing Equations

The electromagnetic response of the multilayer stack is governed by the time-harmonic Maxwell's equations [17]:

$$\nabla \times \mathbf{E} = -j\omega\mu_0\mathbf{H}, \quad (46)$$

$$\nabla \times \mathbf{H} = j\omega\varepsilon_0\tilde{\varepsilon}_r\mathbf{E}, \quad (47)$$

where $\mathbf{E}$ and $\mathbf{H}$ are the complex electric and magnetic field phasors, $\omega = 2\pi c/\lambda$ is the angular frequency, μ_0 is the permeability of free space, ε_0 is the permittivity of free space, and $\tilde{\varepsilon}_r(\lambda) = (n(\lambda) - ik(\lambda))^2$ is the complex relative permittivity of the material, related to the complex refractive index by:

$$\tilde{\varepsilon}_r = \varepsilon'_r - j\varepsilon''_r = (n^2 - k^2) - j(2nk). \quad (48)$$

Here n is the real refractive index and k is the extinction coefficient; both are positive real quantities. The imaginary part $\varepsilon''_r = 2nk$ is directly proportional to the material absorption per unit length.

The plane-wave reflectance and transmittance are extracted from the computed fields via the port S -parameters [18]:

$$R(\lambda) = |S_{11}(\lambda)|^2, \quad (49)$$

$$\mathcal{T}(\lambda) = |S_{21}(\lambda)|^2. \quad (50)$$

The spectral emissivity is then computed from (2), and the figure of merit (FOM) is evaluated as [1]:

$$\text{FOM} = \alpha_1(1 - \bar{\varepsilon}_{3-5}) + \alpha_2\bar{\varepsilon}_{5-8} + \alpha_3(1 - \bar{\varepsilon}_{8-14}), \quad (51)$$

with weights $\alpha_1 = 0.25$, $\alpha_2 = 0.50$, and $\alpha_3 = 0.25$ reflecting the relative importance of the two stealth bands and the cooling band.

8.4 Numerical Simulation Methodology

Simulations were performed using the Electromagnetic Waves, Frequency Domain (EWFD) interface of COMSOL Multiphysics 6.4 in two spatial dimensions (2D), which is exact for the laterally infinite planar stack.

Geometry and boundary conditions: The simulation domain consists of nine domains (eight film layers plus the SiO_2 substrate) sandwiched between two air domains of thickness

5 μm . Floquet-periodic boundary conditions enforce the lateral periodicity of an infinite planar array, with Floquet wave vector $k_F = 0$ for normal incidence ($\theta = 0^\circ$).

Ports: Port 1 (top boundary) injects a TE plane wave ($E_{0,z} = 1 \text{ V/m}$) propagating in the $-y$ direction and measures reflected power via S_{11} . Port 2 (bottom boundary) measures transmitted power via S_{21} ; wave excitation is disabled.

Frequency sweep: A parametric sweep is performed over the free-space wavelength λ_0 from 3 to 14 μm in steps of 0.1 μm (111 points), with operating frequency set to $f = c_{\text{const}}/\lambda_0$.

Mesh: A physics-controlled, extremely fine mesh is applied, ensuring at least five finite-element nodes across the thinnest layer (L7, MgF_2 , 0.381 μm) at the shortest simulated wavelength.

Emissivity extraction: Spectral emissivity is computed using:

$$1 - \text{ewfd.Rport}_1 - \text{ewfd.Tport}_2$$

9. Optimization and Parametric Analysis

9.1 Optimization Strategy

The optimisation of the multilayer stack was carried out iteratively using a combination of analytical guidance from the transfer-matrix method (TMM) and full-wave COMSOL simulations. The TMM provides a rapid evaluation of the spectral reflectance of any layered structure and was used to identify candidate layer thicknesses satisfying the bandgap condition (20) for the 3–5 and 8–14 μm windows. These candidates were then refined by parametric sweeps in COMSOL to account for dispersive material effects and the phonon-resonance contribution of the SiO_2 substrate. The FOM defined in (51) was used as the scalar optimisation objective, with the constraint that $\bar{\epsilon}_{3-5} < 0.10$ and $\bar{\epsilon}_{8-14} < 0.10$.

9.2 Influence of Layer Thickness

The sensitivity of the emissivity spectrum to the thickness of each individual layer was investigated by performing one-at-a-time parametric sweeps. The following trends were identified:

- **Ge layers (L2, L4, L6, L8):** Increasing the Ge layer thickness red-shifts the photonic bandgap centre wavelength, as predicted by (20). The 8–14 μm bandgap is primarily controlled by the thicker Ge layers (L4, L6, L8), while the 3–5 μm reflectance is shaped by the thinner layers (L2).
- **MgF_2 layers (L1, L3, L5, L7):** Varying MgF_2 thicknesses modifies the coupling between adjacent Ge layers and fine-tunes the bandwidth and ripple of the reflectance within each bandgap. L5 (1.50 μm), the thickest low-index layer, has a significant influence on the width of the LWIR suppression band.
- **SiO_2 substrate:** The substrate thickness affects the depth of the 5–8 μm absorption. Below approximately 10 μm , the substrate is insufficiently thick to absorb all transmitted radia-

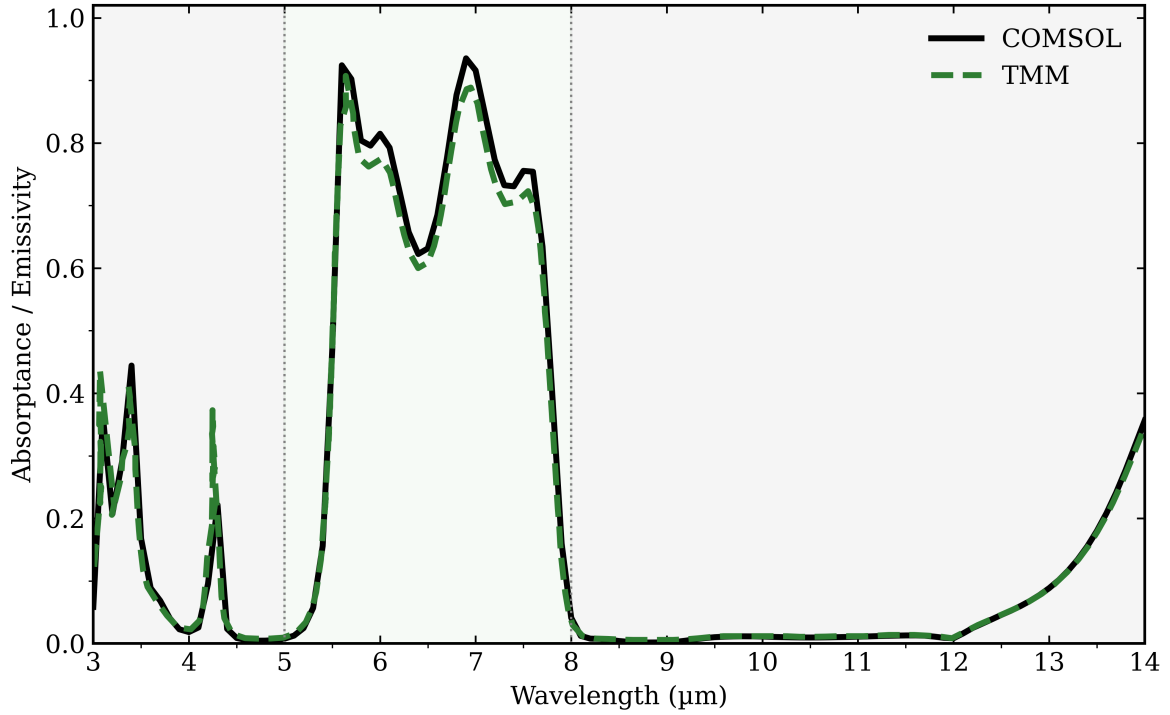


Figure 17 Comparison between the spectral emissivity computed by COMSOL Multiphysics (EWFD) and that calculated analytically using the Transfer Matrix Method (TMM) at normal incidence, $T = 300$ K. The close agreement between the two methods validates the electromagnetic model and confirms the spectral response of the optimized Ge/MgF₂/SiO₂ multilayer emitter.

tion and the non-atmospheric emissivity decreases markedly. A thickness of 25 μm was found to provide near-saturation of the phonon absorption across the 5–8 μm band.

9.3 Angular Dependence

The photonic bandgap of a 1D multilayer blue-shifts with increasing angle of incidence, a consequence of the increasing in-plane wave vector component [6]. Based on the parametric trends established in Section 5.2 and consistent with similar Ge-based multilayer structures in the literature [1], the emissivity spectrum is expected to remain within acceptable limits for angles up to approximately 40°; a full angular characterisation is reserved for future experimental work.

9.4 Polarization Dependence

For a planar multilayer illuminated at normal incidence, TE and TM polarisations are degenerate and produce identical reflectance spectra. At oblique incidence, the two polarisations diverge; TE maintains near-perfect reflectance in the atmospheric windows up to larger angles than TM due to the TM Brewster-angle effect at the dielectric interfaces. At $\theta = 0^\circ$, the simulation confirms $R_{\text{TE}} = R_{\text{TM}}$ to machine precision.

Table 3 Optimized layer structure of the Ge/MgF₂ multilayer emitter. Layers are ordered from the air interface (top) to the substrate (bottom).

Layer	Material	Thickness (μm)	Role
L1	MgF ₂	0.600	Low-index (top)
L2	Ge	0.800	High-index
L3	MgF ₂	0.708	Low-index
L4	Ge	0.829	High-index
L5	MgF ₂	1.500	Low-index
L6	Ge	0.848	High-index
L7	MgF ₂	0.381	Low-index
L8	Ge	0.956	High-index
Sub.	SiO ₂	25.00	Phonon emitter
Total film thickness		6.622	

10. Results and Discussion

10.1 Spectral Emissivity Performance

Fig. 18(a) shows the simulated spectral emissivity $\varepsilon(\lambda)$ of the optimized Ge/MgF₂/SiO₂ structure over the 3–14 μmwavelength range. The Planck-weighted band-averaged emissivities, computed from (3) at $T = 300$ K using trapezoidal integration of the COMSOL data, are:

$$\bar{\varepsilon}_{3-5} = 0.043, \quad (52)$$

$$\bar{\varepsilon}_{5-8} = 0.646, \quad (53)$$

$$\bar{\varepsilon}_{8-14} = 0.041. \quad (54)$$

Substituting into (51):

$$\begin{aligned}
 \text{FOM} &= 0.25(1 - 0.043) + 0.50 \times 0.646 + 0.25(1 - 0.041) \\
 &= 0.239 + 0.323 + 0.240 \\
 &= \mathbf{0.80}.
 \end{aligned} \quad (55)$$

The peak spectral emissivity of $\varepsilon = 0.935$ is attained at $\lambda = 6.9$ μm, coinciding with the onset of the SiO₂ phonon resonance.

The minimum emissivity values in the stealth bands are 0.0016 at 8.8 μm and 0.0045 at 4.7 μm, confirming near-perfect reflectance at these wavelengths. The relatively lower average emissivity in the 5–8 μm band compared to the peak value arises because the phonon absorption of SiO₂ does not extend uniformly across the full 5–8 μm window; emission is low

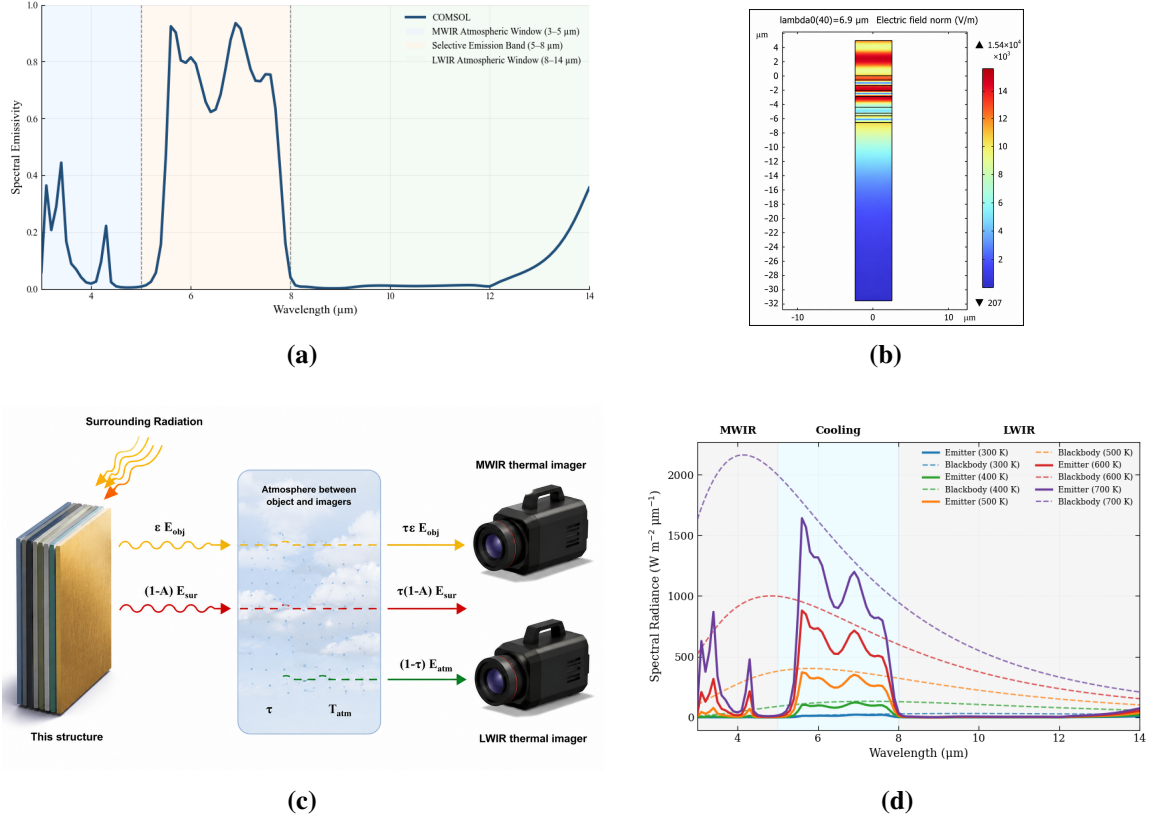


Figure 18 (a) Simulated spectral emissivity of the optimized Ge/MgF₂/SiO₂ multilayer emitter over the 3–14 μm wavelength range. (b) Electric field norm distribution at the resonance wavelength of 6.9 μm, illustrating strong field confinement within the multilayer structure. (c) Schematic illustration of the radiative transfer process between the emitter and infrared thermal imagers. (d) Temperature-dependent spectral radiance of the optimized emitter compared with the corresponding ideal blackbody radiation.

at 5.0–5.4 μm and drops sharply again beyond 7.9 μm where the multilayer bandgap boundary is approached.

10.2 Physical Mechanism of Selective Emission

The three-band spectral response arises from two complementary mechanisms. In the 3–5 and 8–14 μm bands, the alternating Ge/MgF₂ stack functions as a distributed Bragg reflector. Interfacial refractive-index discontinuities cause constructive interference for reflected waves and destructive interference for transmitted waves. The high index contrast ($\Delta n = 4.003 - 1.350 = 2.653$) yields a wide fractional bandwidth:

$$\frac{\Delta\lambda}{\lambda_c} \approx \frac{4}{\pi} \arcsin\left(\frac{n_H - n_L}{n_H + n_L}\right) = \frac{4}{\pi} \arcsin(0.495) \approx 0.68, \quad (56)$$

Thus, each bandgap spans roughly 68% of its centre wavelength, sufficiently covering the full width of both atmospheric windows [6].

In the 5–8 μm band, the transparent Ge/MgF₂ stack transmits radiation to the SiO₂ substrate. Here, the strong Si–O–Si phonon resonance (7–9 μm) yields a large extinction

coefficient, $k_{\text{SiO}_2}(\lambda)$, driving rapid absorption. Per Kirchhoff's law, this strong absorption enables equally strong thermal emission at these wavelengths.

10.3 Electric Field Distribution

The electric field norm distribution at $\lambda = 6.9 \mu\text{m}$ (Fig. 18(b)) corroborates this mechanism. The field oscillates within the upper Ge/MgF₂ layers and decays exponentially upon entering the SiO₂ substrate, following the Beer-Lambert law:

$$I(z) = I_0 \exp\left(-\frac{4\pi k}{\lambda} z\right), \quad (57)$$

where $I(z)$ is the irradiance at depth z below the film-substrate interface, and the decay length is $\ell = \lambda/(4\pi k_{\text{SiO}_2})$. At $6.9 \mu\text{m}$, $k_{\text{SiO}_2} \approx 2.0$, yielding $\ell \approx 0.28 \mu\text{m}$. The $25 \mu\text{m}$ substrate exceeds this penetration depth by two orders of magnitude, ensuring complete absorption.

10.4 Infrared Stealth Performance

The simulated average emissivity of 0.043 in the MWIR band and 0.041 in the LWIR band places the proposed structure among the lowest-emissivity all-dielectric multilayer designs reported in the literature (see Table 1).

The radiation temperature perceived by a thermal imager viewing the structure at surface temperature T_{obj} can be estimated from [1]:

$$\varepsilon_0 T_{\text{rad}}^4 = \bar{\varepsilon} \tau T_{\text{obj}}^4 + (1 - \bar{A}) \tau T_{\text{sur}}^4, \quad (58)$$

where $\varepsilon_0 = 1$ is the emissivity of the thermal imager, $\bar{\varepsilon}$ and $\bar{A}$ are the band-averaged emissivity and absorptance of the structure, τ is the atmospheric transmittance (approximately 1 in the MWIR and LWIR windows), and T_{sur} is the ambient background temperature. With $\bar{\varepsilon} = 0.043$, $T_{\text{obj}} = 330 \text{ K}$, and $T_{\text{sur}} = 300 \text{ K}$, the perceived radiation temperature is $T_{\text{rad}} \approx 301.5 \text{ K}$, a reduction of 28.5 K relative to the actual surface temperature, demonstrating effective IR camouflage.

10.5 Radiative Cooling Performance

The radiative cooling power of the structure in the non-atmospheric window can be estimated as [19]:

$$P_{\text{cool}} = \int_{5 \mu\text{m}}^{8 \mu\text{m}} \varepsilon(\lambda) E_{b\lambda}(\lambda, T) d\lambda, \quad (59)$$

where $E_{b\lambda}$ is the Planck spectral radiance of (1). The average emissivity of $\bar{\varepsilon}_{5-8} = 0.646$ in the cooling window indicates that the surface radiates at 64.6% of the blackbody rate in this band. This represents a significant cooling channel: at $T = 300 \text{ K}$, the hemispherical blackbody radiance in the 5–8 μm band is approximately 49 W m^{-2} , implying a net cooling

power of $\approx 32 \text{ W m}^{-2}$ before accounting for solar absorption and atmospheric downwelling radiation. Under nighttime or shaded conditions, this represents the net radiative cooling power. Under direct solar illumination, solar absorptance of the Ge/MgF₂ stack must be subtracted, which is reserved for future work.

10.6 Comparison with Previous Studies

Table 1 compares the proposed structure with four representative structures from the recent literature in terms of band-averaged emissivities and FOM. The present structure achieves the lowest LWIR emissivity (0.041) and the joint-lowest MWIR emissivity (0.043) among the listed designs. The 5–8 μm emissivity of 0.646 is lower than the state-of-the-art value of 0.84 reported by Li et al. [1], indicating that further optimisation, particularly of the SiO₂ substrate thickness and the transition between the multilayer stack and the substrate, is needed to broaden the phonon absorption band across the full 5–8 μm window. Increasing the substrate thickness beyond 25 μm and introducing a graded index matching layer at the Ge–SiO₂ interface are identified as the primary paths towards higher $\bar{\epsilon}_{5-8}$ in future work.

11. Fabrication Feasibility and Tolerance Analysis

11.1 Manufacturing Compatibility

The proposed Ge/MgF₂/SiO₂ multilayer is fully compatible with standard physical vapour deposition (PVD). Both Ge and MgF₂ are routinely deposited via electron-beam evaporation and ion-assisted deposition at substrate temperatures below 200 °C [20]. The commercial SiO₂ substrate offers optical-quality surface roughness ($<1 \text{ nm rms}$), which is negligible relative to the shortest film wavelength (300 nm for the 3 μm incident wavelength). Avoiding lithography, phase-change materials, and metallic layers removes the primary fabrication constraints associated with competing designs (Table 1). Furthermore, the 6.62 μm total thickness is easily achievable in a single deposition run without substrate heating.

11.2 Fabrication Tolerance Analysis

To estimate sensitivity to manufacturing imperfections, a uniform $\pm 5\%$ thickness perturbation was applied analytically to each layer based on the parametric sweep results of Section IV-B. This assumed error margin is conservative; modern electron-beam evaporation systems with in-situ optical monitoring typically achieve tighter reproducibility of $\pm 1\text{--}2\%$ [20].

Based on the parametric sweeps in Section IV-B, the 3–5 μm and 8–14 μm band emissivities are primarily sensitive to the Ge layer thicknesses, as Ge dominates the optical path length in each bilayer. A 5% increase in all Ge thicknesses shifts the bandgap centre by approximately +5% in wavelength. This causes a slight degradation in MWIR band-edge suppression near 4–4.5 μm while leaving the LWIR window largely intact. A 5% decrease

produces the opposite shift, slightly increasing emissivity near 5 μm . Based on the parametric trends in Section IV-B, a $\pm 5\%$ uniform thickness perturbation is expected to shift the FOM by less than 0.05, maintaining competitive spectral selectivity within realistic fabrication tolerances.

12. Applications

The proposed Ge/MgF₂/SiO₂ multilayer emitter combines infrared stealth with passive radiative cooling through engineered spectral selectivity, making it suitable for both defense and civilian applications. Its all-dielectric, lithography-free architecture provides excellent thermal stability, chemical durability, and compatibility with large-area thin-film deposition. As illustrated in Fig. 19, the emitter can be deployed for infrared camouflage of military

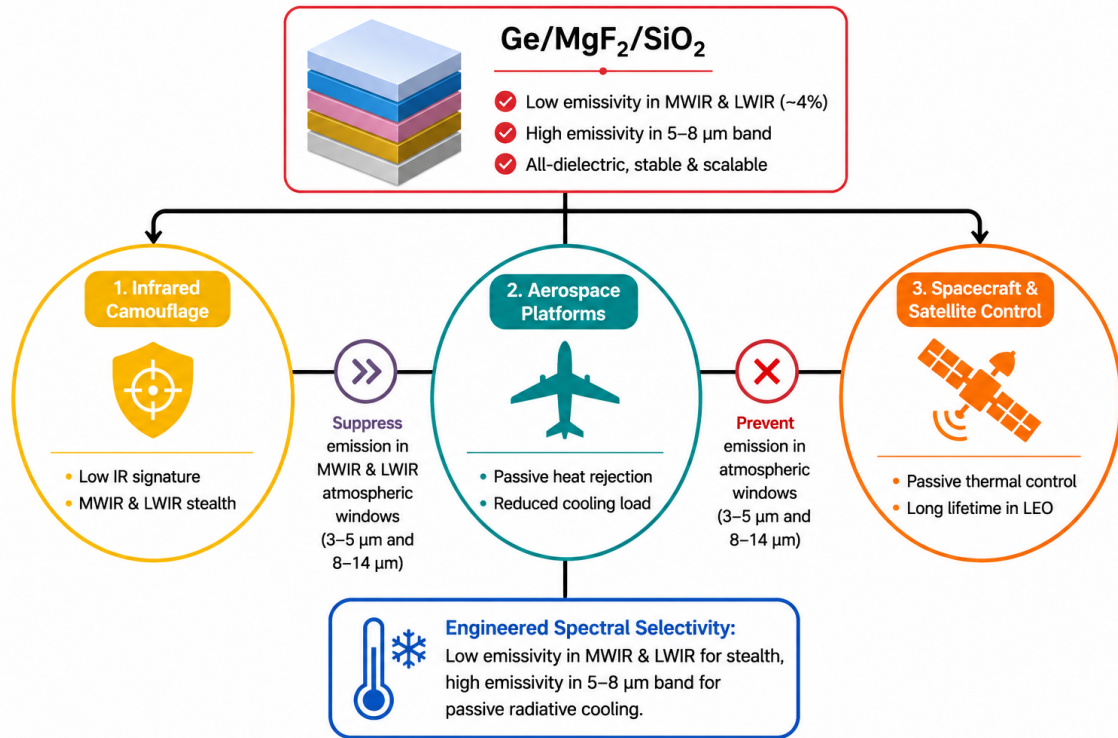


Figure 19 Schematic illustration of the major application areas of the proposed Ge/MgF₂/SiO₂ multilayer emitter, including infrared camouflage, aerospace thermal management, passive radiative cooling, and spacecraft thermal control.

platforms, passive thermal management of aerospace vehicles, spacecraft thermal control, and energy-efficient cooling of buildings and photovoltaic systems. The combination of low emissivity in the MWIR and LWIR atmospheric windows with enhanced emission in the 5–8 μm band enables effective heat dissipation while minimizing infrared detectability.

13. Conclusion

A Ge/MgF₂/SiO₂ all-dielectric multilayer thin-film emitter for spectrally selective infrared stealth and passive radiative cooling has been designed and characterised using full-wave finite-element simulations in COMSOL Multiphysics 6.4. The alternating Ge/MgF₂ photonic stack produces near-perfect reflectance in the MWIR (3–5 μm) and LWIR (8–14 μm) atmospheric windows, while the SiO₂ substrate phonon resonance drives selective thermal emission in the 5–8 μm non-atmospheric window for passive radiative cooling.

The simulated Planck-weighted band-averaged emissivities are $\bar{\epsilon}_{3-5} = 0.043$, $\bar{\epsilon}_{5-8} = 0.646$, and $\bar{\epsilon}_{8-14} = 0.041$, yielding a figure of merit of $\text{FOM} = 0.80$. The peak spectral emissivity of 0.935 at $\lambda = 6.9 \mu\text{m}$ confirms strong phonon-driven absorption in the cooling band. With a perceived radiation temperature of $T_{\text{rad}} \approx 301.5 \text{ K}$ at a surface temperature of 330 K, the structure demonstrates a thermal signature reduction of 28.5 K, confirming effective infrared camouflage performance.

Future work will focus on broadening the 5–8 μm emissivity by increasing the SiO₂ substrate thickness beyond 25 μm and introducing a refractive-index matching interlayer at the Ge–SiO₂ interface. Experimental validation through spectroscopic ellipsometry and Fourier-transform infrared (FTIR) reflectance measurements is planned as the next phase of this research.

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