Le Laboratoire de Physique du Rayonnement et de la Lumière

(The Laboratory of the Physics of Light and Radiation)

Stealth coatings technology section

Theory, measurements and electromagnetic's characteristics

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Overview of LPRL

The Laboratoire de Physique du Rayonnement et de la Lumière (LPRL) is organized as a Société Civile d'Etude et de Recherche under French law. It is a private research and development company founded in 1992 and based in Paris, France. The strength of LPRL stems from its association of research scientists combined of experience in physics and optics. The activities of the LPRL in the United States are directed by Dr. Brett KRAABEL, Ph.D. in physics from the University of California at Santa Barbara. Director of the laboratory is physicist Philippe Edouard GRAVI SSE assisted by Marc SCHIFFMANN D.es.sc.

The LPRL has developed technologies that currently find uses in applications ranging from plant physiology to infrared (IR) low observable coatings. These technologies may be grouped into the categories listed below:

Energy

1.1 – Photovoltaic power generator "Factor 2" for space and military applications. This technology improves the output conversion and the weight-to-power ratio of photovoltaic cells.
1.2 – Photovoltaic radio generator yielding continuous long-lasting power for space telecommunications applications.

Counter Measures

Military:

2.1 – Laser detection and alert systems
2.2 – 1.064 µm anti-reflection coating to counter laser range-finders
2.3 – Low observable coatings for IR band II radiation – compatible with radar-absorbing materials (RAM)
2.4 – Low observable coatings for IR band III radiation – RAM compatible
2.5 – Heads-up display discretion
2.6 – Laser counter-measure systems for helmet visors or helicopter canopies
2.7 – Multifunction (IR and radar) stealth coatings for electromagnetic counter-measures

Civilian:

2.8 – Stealth fiduciary marking
2.9 – Noncopiable paper
2.10 – Ticket marking
2.11 – Bank card marking
2.12 – Security card marking

Physiology

3.1 – Improvement of plant growth by management of physiological parameters such as photoperiodism and thermoperiodism
3.2 – Materials and coatings with selective emittance to promote photosynthesis

Materials

4.1 – Pholuminescent materials with long or short after-glow
4.2 – Textile photoluminescent enductions with long or short after-glow

Optronics and associated systems

5.1 – Urban PVE modules for polyenergy propulsion (project stage)
5.2 – Energy management for photovoltaic systems using the concept of sequential energy management
5.3 – Systems to detect fiduciary markings (related to the technology 2.8 – 2.12)
5.4 – Electronics associated with the laser detection and alert system (see 2.1)

Spectral analysis of materials UV/Vis/IR (250 nm to 15 μm)

6.1 – Absorbance, transmittance and reflectance spectra
6.2 – Emittance spectra
6.3 – Analysis of spectral distribution of electromagnetic radiation
6.4 – Color analysis (colorimetry)

Partners

LPRL currently holds and manages a portfolio of 29 patent lines resulting from research into the physics of light and radiation. The research has been carried out at the facilities of LPRL and with the collaboration of the following partners:

1) for civilian applications

- RHONE POULENC – specializing in chemistry and photoluminescent properties of materials
- CFP-TOTAL/CDF – specializing in photovoltaics and associated systems
- BIOCUBE – 2nd generation photovoltaics and associated electronics
- ELF-AQUITAINE – light cascade materials for agricultural greenhouses
- BANK OF FRANCE – stealth fiduciary marking
- MIR, ANVAR, CISI, TELESYSTEME – (Ministry of Industry and Research, National Agency for Promotion of Research, Industrial Technology Services for Data Processing, partners of BRIC/PG for the development of Data Bank Information Technologies such as TRANSINOVE International)
- INPI/ANVAR – Development of TRANSINOVE International data base for technology transfer within the European Union

2) for non-civilian applications

- DGA («Délégation Générale pour l'Armemant» which is the General Commission for Armament)– stealth materials and laser counter-measure systems program "DESIR": (*Décaractérisation de la Signature Infra-Rouge*)
- CREA («Centre de Recherches et d'Etudes de l'Armemant» which is the Center for Armament Research and Development)
- CEA/DAM, ("Centre d'Etudes Atomiques-Direction des Affaires Militaires" which is the Center for Atomic Studies, Military Affaires Section)
- CEA Grenoble
- Opération DESIR (Décaractérisation des Signatures Infrarouges) Stealth coatings matérials IR/RAM and CML 106 (laser counter-measure systems) for DGA
- AEROSPATIALE / HE / EUROCOPTER – IR stealth materials under the TIGRE / HAP 90 program "DESIR",
- AMDBA (Avions Marcel Dassault / Breguet Aviation) - IR Stealth Program "DESIR" for ACF / RAFALE,
- ISO Color – IR/visible gonio-spectrometer

In addition to the companies and institutions listed above, LPRL collaborates with the following laboratories:

- CNRS (Centre National de Recherche Scientifique) Phytotron Laboratory at Gif sur Yvette near Paris
- Centre de Physique Moléculaire et Optique Hertzienne at the University of Bordeaux
- CEA, DAM
- Centre de Physique Moléculaire et Optique Hertzienne at the University of Bordeaux I
- THOMSON-CSF – Optronics division
- THALES (TRT Research Center – Palaiseau)
- Copenhagen Institute of Technology

Review of Stealth Coatings Technologies

Introduction

Stealth using low observable materials enables the control or reduction of the signatures of weapon systems. Signatures are those characteristics by which weapon systems may be detected, recognized, and engaged. The modification of these signatures can improve the survivability of military systems, leading to improved effectiveness and reduced casualties as demonstrated in the Persian Gulf conflict.

Signature detection commonly amounts to the detection of the electromagnetic signature of an object. Figure 1 shows a schematic of the electromagnetic spectrum. The spectral regions of interest for low observable technologies are the visible range, the infrared (IR) range (particularly bands II and III which are shown in Figure 1), and the radar portion of the spectrum in the GHz regime. In addition the wavelength of 1.064 µm is of interest as it is the wavelength of Nd:YAG lasers from which the majority of laser range-finders are fabricated.

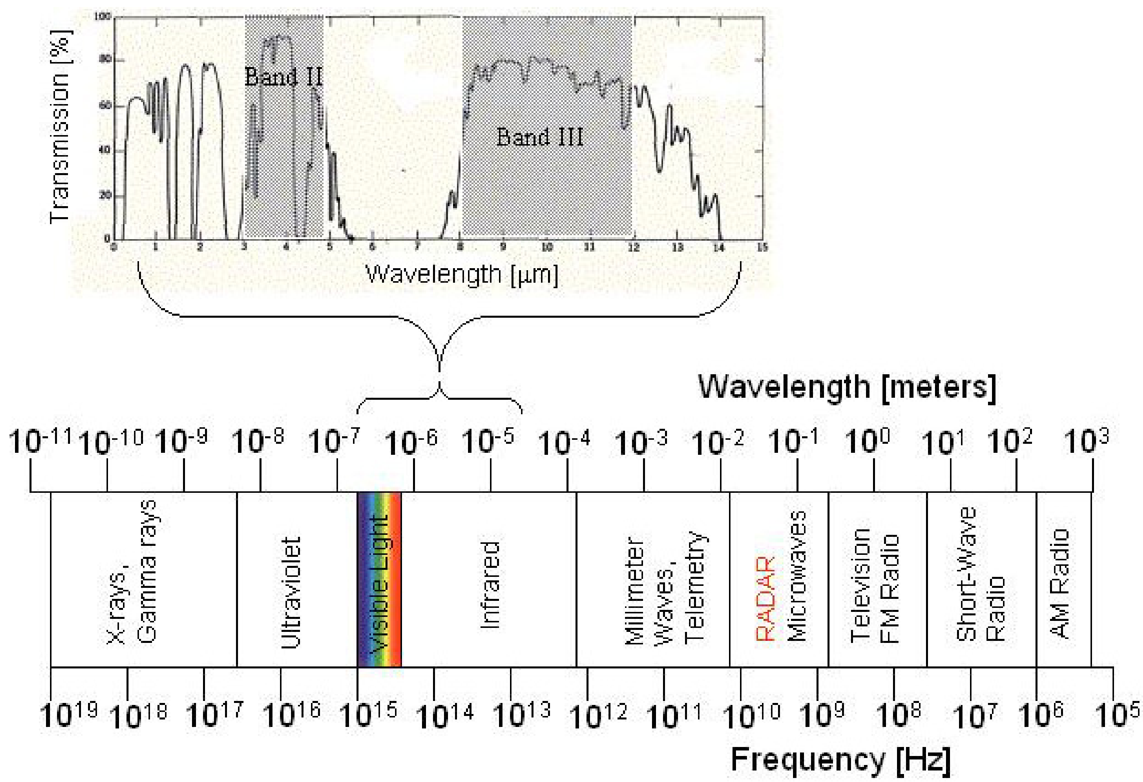

Figure 1: The electromagnetic spectrum with the infrared portion of the spectrum expanded. The expanded portion of the spectrum shows the percent atmospheric transmission through 6,000 horizontal feet at sea level

The emphasis to date has been on radar stealth, and thus radar-absorbing materials have received significant attention. However, with the development of infrared (IR) detection technology such as missile guidance systems and thermal cameras, the need for effective IR stealth capabilities is pressing for air, land, and sea defenses.

LPRL stealth coatings are multipurpose materials that may be tuned for specific missions, or used in standard configurations. For example, they may be designed with tailored emissivities in bands II and III (without compromising RAM properties) for specific missions, or they may be combined with radar absorbing materials to produce multipurpose coatings that address IR and radar stealth simultaneously. LPRL also designs coatings that provide an effective counter measure against laser range-finders and that are compatible with IR stealth coatings and RAM.

Below we give a brief description of current techniques for IR and radar stealth, following which we describe LPRL technology in this area.

Infrared Stealth

IR discretion techniques focus on bands II and III which are transmission bands in the earth's atmosphere (see Figure 1). Band II covers the range from 3 to 5 µm while band III covers the range from 8 to 12 µm. Band II is exploited primarily by missile guidance systems and band III by thermal cameras. Another wavelength of interest is 1.064 µm, which is the wavelength used by the majority of laser range-finders.

Current technologies for IR stealth may be grouped into the following categories.

Luring

The original means of luring first generation missiles (missiles whose guidance systems operated in band I – 1 to 2.5 µm) consists of flying the aircraft towards the sun, if possible, then performing a drastic evasive maneuver in the hopes that the missile's guidance system would lock onto the signal coming from the sun. Another technique involves flying in pairs along the same direction, but separated by several miles. The trailing aircraft performs an evasive maneuver in the hopes that the missile locks onto the lead aircraft, which is beyond the missile's range.

Second generation guidance systems operate in band II and are not deceived by the techniques described above. One deception technique useful against these systems is the launching of thermal lures by the aircraft in such a way as to lure the missile toward the false target. This technique proves relatively ineffective against guidance systems that contain imaging capabilities since these systems allow the missile to remain locked onto the original thermal image of the aircraft.

Possible means of evading these missiles include modifying the thermal image of the aircraft, reducing the thermal emission of the aircraft to make detection more difficult, or increasing the thermal emission of the aircraft in order to saturate the missile's detectors.

Low emittance materials

Current low emittance materials are based upon conductive materials such as aluminum alloys with varying geometries and granularity. These materials are suspended in a varnish that is painted onto the equipment. This approach proves economically attractive but suffers from two major disadvantages.

- It is possible to recreate the real temperature of an object from a spectral analysis of the emission.
- A high concentration of the active substance is needed to achieve a low emittance, which in turns compromises any pre-existing RAM properties.
- The low emissivity covers a portion of the electromagnetic spectrum larger than necessary (i.e. band II), resulting in an undesirable rise in substrate temperature and subsequent increased emission. The rise in substrate temperature may also induce further complications due to sensitive equipment, coatings, etc.

Active Cooling Mechanisms

A technique to decrease the temperature of hot gases expelled by engines is to inject cold air into the hot gas stream. The majority of aircrafts that enjoy a reduced radar cross-section (RCS) use this technique. However, this technique prevents manufacturers from exploiting post-combustion, hence reducing the maximum thrust achievable with these engines.

Thermal Insulating Materials

It is possible to place thermal insulating materials over a thermal source to alter its IR signature. However, a disadvantage of this strategy is that the temperature of the thermal source will rise, resulting in possible damage to the source (it may contain sensitive electronics or mechanical components). In addition, it is difficult to maintain large thermal gradients over thicknesses comparable to that of typical IR stealth coatings, so that thermal insulating materials often come with a high thickness and weight penalty.

Radar Stealth

We discuss here several existing technologies that address the problem of radar stealth.

Stealth Geometry

The principle of this technology consists of designing the exterior geometry of a mobile or stationary unit to reflect radar radiation in a direction that makes it difficult to detect. A drawback of this technology is that it imposes geometrical constraints that may decrease the performance of airborne units. Examples of this include the F117 that is not supersonic because of its stealth geometry, and the modifications of the air entries of the B1 which reduced the RCS but cost 0.4 mach. Geometrical constraints prove less problematic for ships, land vehicles and stationary infrastructure.

Radar Absorbing Materials (RAM)

RAM may be applied to critical parts of air born units as well as to land vehicles and infrastructure. An inconvenience of this type of treatment is that it is not effective against all radar frequencies. In addition, for longer wavelength radar the thickness of the coatings must increase (increasing the weight of the coating as well). The active materials used in RAM consist of different types of ferrites as well as conducting polymers such as polyaniline or polypyrrole.

Active Neutralization

The technology of neutralization consists of analyzing the radar environment in which a unit is immersed in order to generate and emit a radar signal of equal magnitude but opposite phase resulting in the nullification of the total radar signal reflected by the unit. This system can be adapted to all radar frequencies but requires powerful calculation capabilities in order to analyze the radar environment in real-time. In addition the problem of emitting a multitude of radar frequencies is currently not resolved, especially for aircraft.

Luring or Deception

Currently the main technique used for luring involves launching a packet of chaff from the unit being targeted in order to create a secondary radar image that overwhelms the original image. This technique is problematic for naval vessels due to the possibility of variable winds that may blow the chaff in undesirable directions. In addition certain missiles are equipped to counter this lure and to remain locked onto the original target.

LPRL Stealth Coatings Technology

Infrared Stealth

LPRL IR stealth coating technology alters the thermal emissivity of a host. Emissivity is defined as the ratio of radiant energy emitted by a body to the radiant energy emitted by a black body at the same temperature. Formally,

$$\varepsilon = W_{graybody} / W_{blackbody}$$

where ε is the emissivity, and $W_{gray\ body}$ ($W_{black\ body}$) is the total radiant energy emitted by a gray body (black body) at a given temperature. Hence an emissivity of unity corresponds to a perfect black body, while an emissivity of 0 corresponds to a completely non-emissive material.

The radiation emitted by a black body is described by Planck's Law and is shown below in Figure 2 for several temperatures. As the temperature increases, the peak emission wavelength shifts towards the blue. This is known a Wien's law, and is described by the formula

where $\lambda_{\max}$ is the wavelength in microns of the peak of the radiant emittance and T is the temperature in Kelvin.

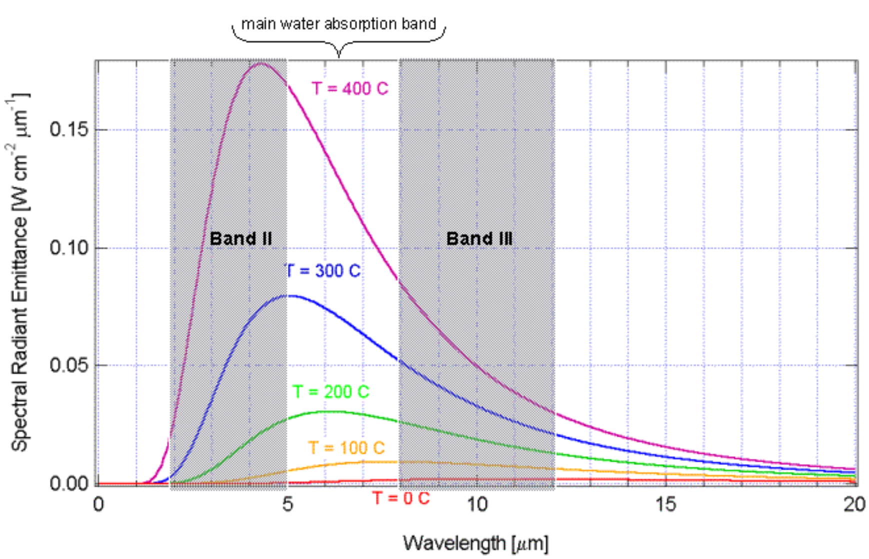

Figure 2: Spectral radiant emittance from a black body at several temperatures.

LPRL IR stealth coatings exploit LPRL's patented narrow-band selective emissivity technology, which enable our coatings to shift the energy of the emitted radiation outside the detectable band.

For example, we show below the spectral radiant emittance from a body at 700 K (427 C) that is coated with a coating of LPRL low observable paint, and the same thing coated with a broad-band metallic-based low observable paint. Note that the emittance from the LPRL coated object is reduced in band II (3 to 5 mm), and is increased outside of this band (red curve is above black dashed curve outside of band II). The same object coated with a metallic-based low emissivity coating also emits less in band II (although not to the extent of the LPRL coating), but does not shift the emittance into the atmospheric absorption band (5 to 10 mm) as does the LPRL coating. In addition, since the broad-band coating acts as a thermal insulator, the temperature of the underlying object is increased to a much greater extent than for the LPRL coating.

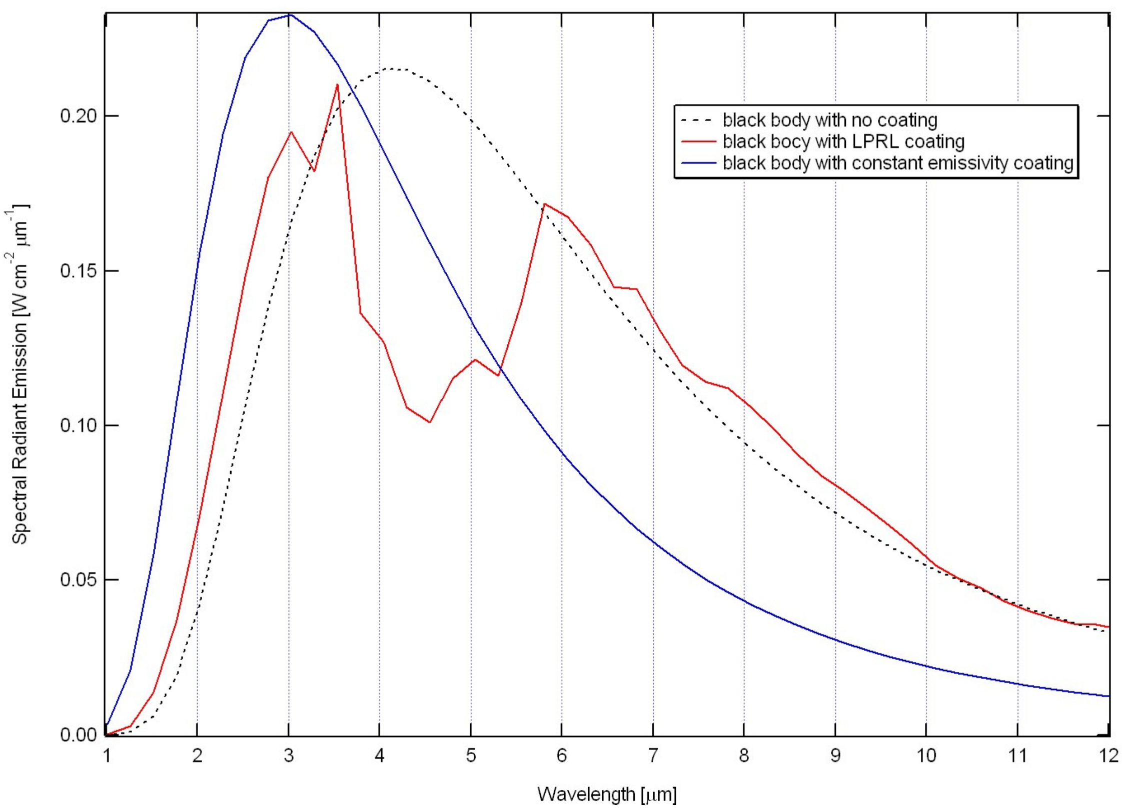

Figure 3: The spectral radiant emittance from a 1 cm black body cube heated to 700 K (427 C, dashed curve), the same cube coated with an LPRL low emissivity coating (red curve), and coated with a broad-band metallic-based low emissivity coating (blue curve).

The LPRL coating not only render IR detection more difficult by reducing the emission in band II, but, by perturbing the spectral distribution of the emitted radiation, also deceives thermal images that rely on reference spectra to arrive at the brightness temperature of an object. In addition, being non-metallic in nature, LPRL low emissivity coatings are also compatible with radar absorbing materials (RAM), and may therefore be used in multipurpose coatings (IR/RAM), which we describe in more detail below.

Together with industrialists specialized, LPRL has perfected a suite of low emissivity coatings with average emissivities in Band II ranging from 0.40 to 0.80 (see Figure 5). In addition we show the average emissivity from 3.7 to 4.7 mm, where a majority of thermal detectors operate.

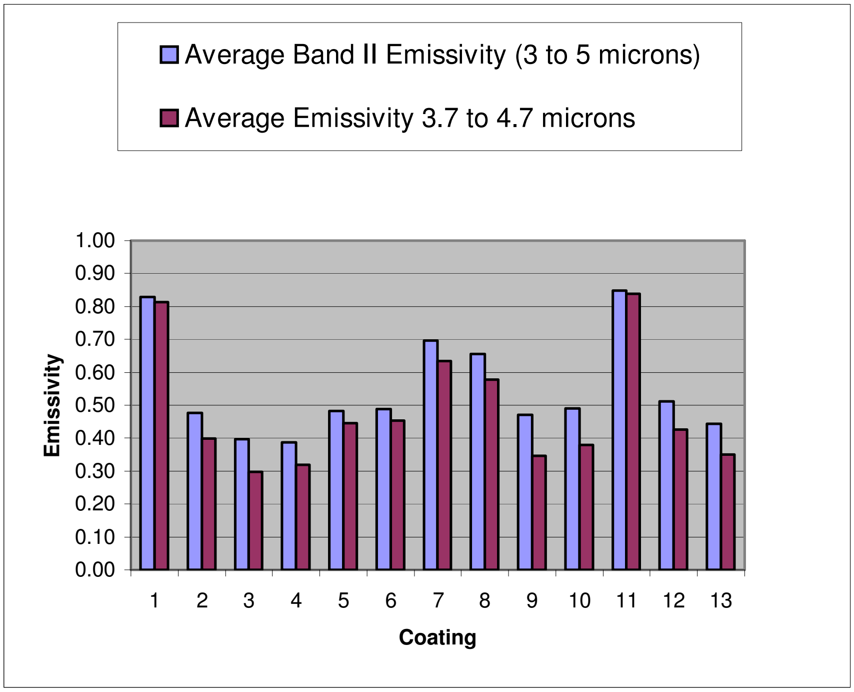

Figure 4: The emissivity of a selection of LPRL low emissivity coatings.

One of several independent confirmations of the potential of LPRL IR stealth coatings is shown below in Figure 5 which shows the results of a thermal image measurement in band II made by Giat Industries[1] . The sample shown is coated with a standard NATO coating. In the lower-left quadrant of the sample an LPRL IR stealth coating is deposited over the NATO coating. Since the sample was positioned vertically in an oven, there is a slight vertical thermal gradient present, so comparisons should be made between regions of the sample that are at the same vertical position. As the temperature scale is difficult to read, we note that the apparent temperature difference between the LPRL coated portion of the sample and portion of the sample coated with the standard NATO coating is approximately 12 degrees Celsius (from roughly 57 to 69 degrees Celsius). This apparent temperature difference increases for higher substrate temperatures. For example, at 150 degrees Celsius, an apparent temperature difference of 16 degrees Celsius is measured between portions of the same sample when one portion is coated with an LPRL coating and the other with a NATO standard coating.

[1] www.giat-industries.fr/

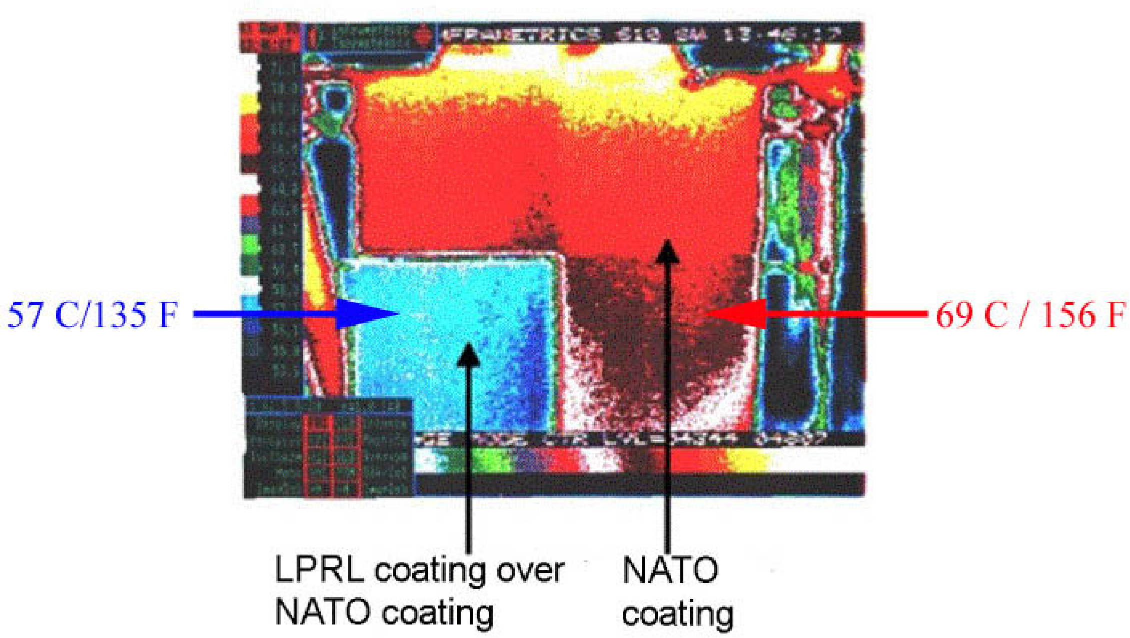

Figure 5: A band II thermograph of a substrate coated with the standard NATO coating and an LPRL IR low emissivity coating. The apparent temperature of two regions of the sample that are at the same actual temperature is noted in the figure.

In addition to band II coatings, LPRL has developed coatings that address band III. A band III thermograph of the coating applied over a NATO black coating is shown below, and demonstrates that the LPRL band III coating lowers the brightness temperature detected by the thermal camera.

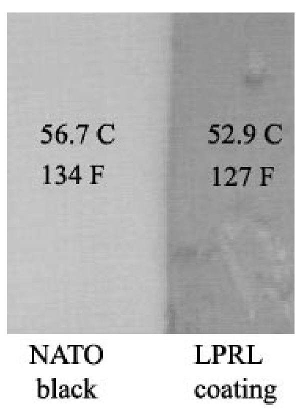

Figure 6: A band III thermograph of an Al coupon coated with a NATO black paint, on top of which is a LPRL coating.

Some key characteristics of these band II/III coatings are given in Table 1 below:

Table 1:Characteristics of LPRL band II/III coating.

Parameter	Value
ε Band II [max, min]	0.56 < ε < 0.62
ε Band III [max, min]	0.72 < ε < 0.77
Usable Temperature Range [C] / [F]	150 / 300
Min. Thickness [μm] / [mil]	50 / 2
Density [gm/cm^3]	1.3
Weight Penalty [lbs/ft^2][2]	0.013

By combining coatings with different emissivities in a pattern, the effectiveness of the stealth may be enhanced. The concept is illustrated below, where we illustrate how a tank may be coated with a thermal camouflage pattern with the aim of matching the thermal background.

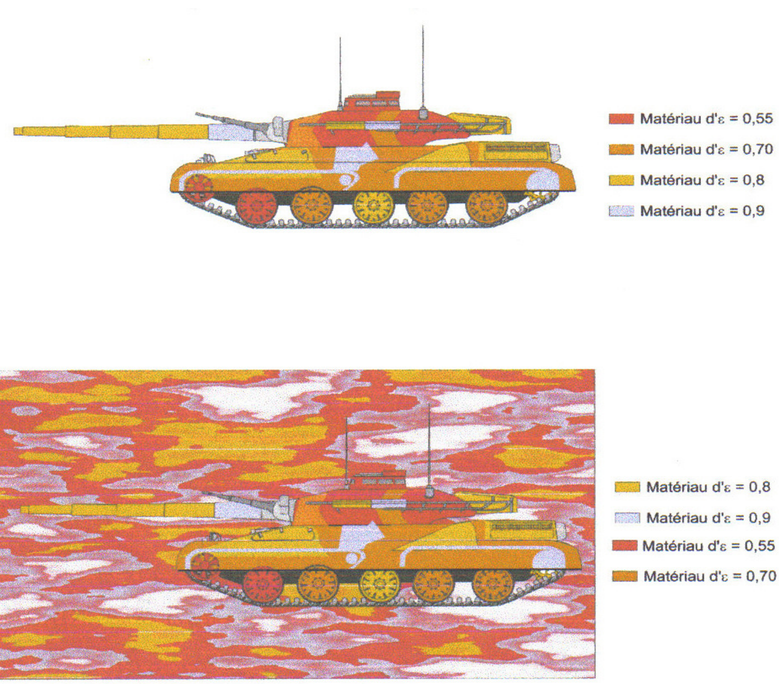

Figure 7: Illustration of how coatings with different emissivities may be used to improve stealth.

2 Assuming minimum thickness.

Combined Infrared and Radar Stealth

To this point, we have discussed IR stealth technology as separate from radar stealth technology. However, in the near future coatings will have to perform both functions simultaneously in order to counter the threat of dual mode missile guidance systems such as the MICA air-to-air missile that equips, among others, the Mirage 2000-5. In general, a unit's coating will need to satisfy the requirements of the missions for which it was designed. For example, ground-support aircraft face very different threats than tanks or ships or aircraft designed with air superiority assumed, and the coatings of each will be different. Certain zones need only an IR stealth or RAM coating, while other zones require a combined IR/RAM stealth coating.

As discussed above in the brief review of stealth technologies, it is difficult to combine IR and radar stealth because many current IR low observable materials are based on conductive elements, which are not RAM. Hence the dielectric nature of the LPRL IR stealth coatings proves advantageous for combined IR/RAM coatings because the active elements that provide IR stealth do not perturb the RAM characteristics. On the contrary, LPRL IR stealth coatings actually provide a modest amount of radar furtivity.

Table 2 below shows the mean attenuation coefficient for a 150 μm thick LPRL IR stealth coating. While the magnitudes of these attenuation coefficients obviously are not sufficient to provide the primary radar stealth properties of a vehicle, they do demonstrate the compatibility of LPRL IR coatings with radar cross-section (RCS) reduction schemes.

		Band [GHz]		
Polarization	Incident Angle	7.5 –12.5	28.5–40.5	75–110
		Mean Attenuation [dB]	Mean Attenuation [dB]	Mean Attenuation [dB]
Horizontal	Normal	0.03	0.3	0.0262
Horizontal	5º	1	1.7	2.28
Horizontal	10º	4.75	6.5	6.25
Vertical	Normal	0.035	0.025	0.05
Vertical	5º	2	1.9	2
Vertical	10º	7.5	7	6.5

Table 2 – The mean attenuation in the GHz range of a 150 μm thick LPRL IR/RAM stealth coating.

To further demonstrate the neutrality of the LPRL IR stealth material in the GHz frequency range, the German firm IBD measured the radar reflectivity of a polyethylene (PE) film before and after coating with an LPRL IR stealth coating. Referring to Figure 8 below, it is seen that the pure PE film has a reflectivity coefficient of approximately –30 dB or less from 8 to 18 GHz. Three LPRL coatings, colored brown, green and sand, are deposited over separate PE films and the radar reflectivity is again measured. The data shown in Figure 8 show that the reflection coefficient remains very low from 8 to 18 GHz, as well as at 35 and 94 GHz (see Table 1).

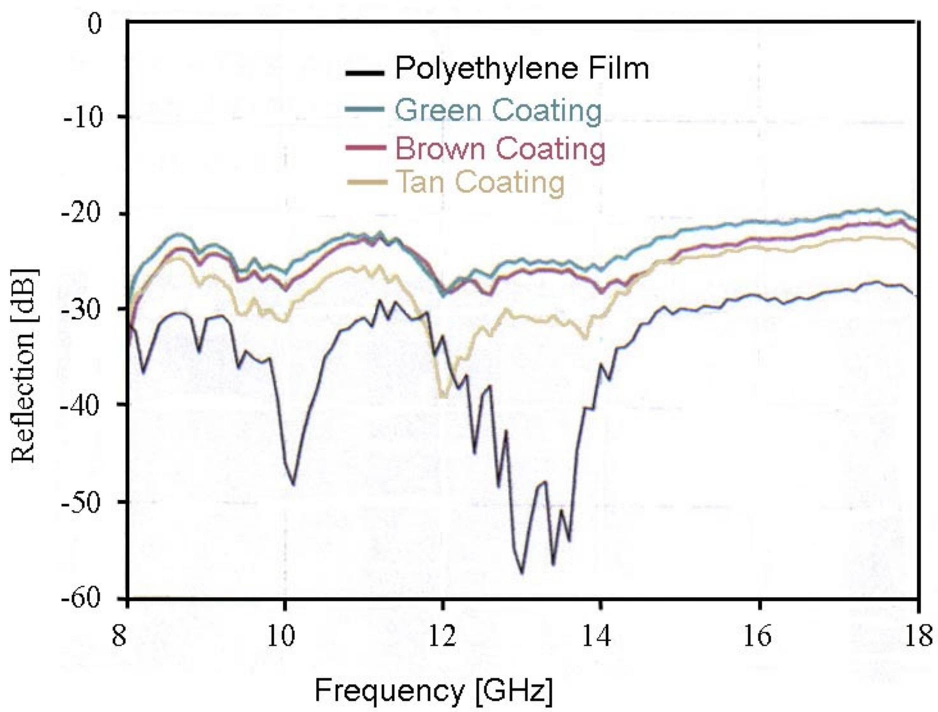

Figure 8: Reflection at near-normal incidence of LPRL coatings deposited over a polyethylene film.

Table 2: Reflection coefficients for a polyethylene film and the same film coated with different color LPRL IR low emissivity coatings.

Visible Color	35 GHz	94 GHz
Brown	-17 dB	-11 dB
Sand	-18 dB	-10 dB
Green	-17 dB	-12 dB
PE film	-26 dB	-17 dB

To provide true multipurpose coatings (combined IR and radar stealth coatings) LPRL IR stealth coatings must be combined with radar absorbing materials, using, for example, either a multilayer or homogeneous approach. The schematic diagram in Figure 9 shows the essence of these two approaches.

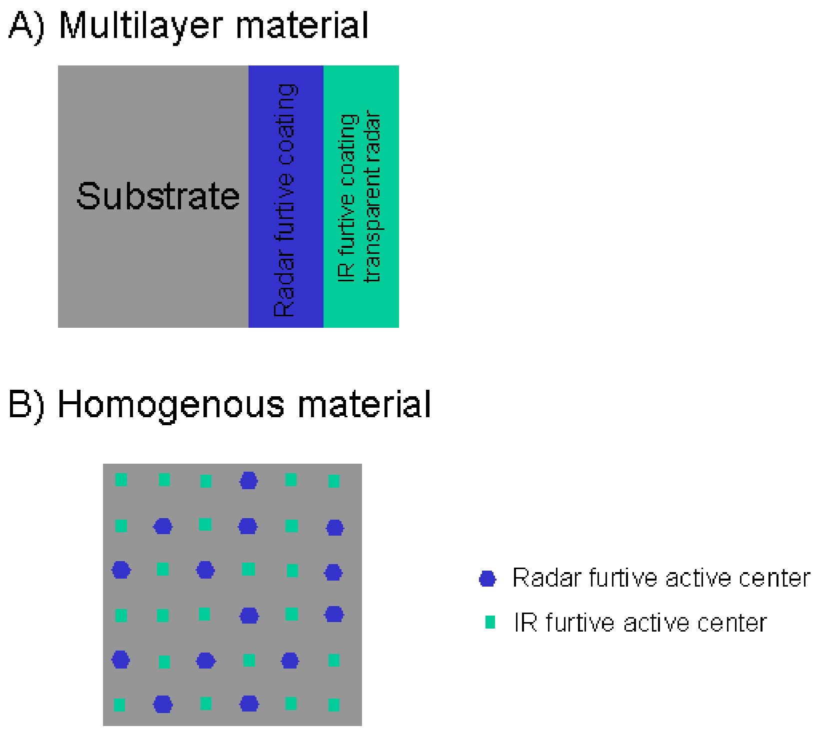

Figure 9: A schematic diagram of two approaches for making dual-purpose coatings (IR and RAM).

The multiplayer architecture consists of applying sequential layers of different coatings. In this approach, the outer layer typically provides the IR stealth properties, without perturbing the RCS of the host. The inner layer is designed to reduce the RCS.

In the homogenous material the active dopants that provide IR or radar stealth are blended together in precise stoichiometric ratios that are varied depending on the application (aircraft, ship, tank…) and/or mission.

The French firm Thales[3] measured the reflectivity of a 10 X 10 cm sample coated with a 1.9 mm thick LPRL IR/RAM homogeneous multipurpose coating. This coating consists of a silicone-based host material doped with spherical ferrites for radar absorption and LPRL additives for IR stealth. Figure 10 shows the radar reflectivity of this sample for three different angles of incidence, and for two different polarization modes (TE-TE in the top panel and TM-TM in the bottom panel).

[3] www.thalesgroup.com/

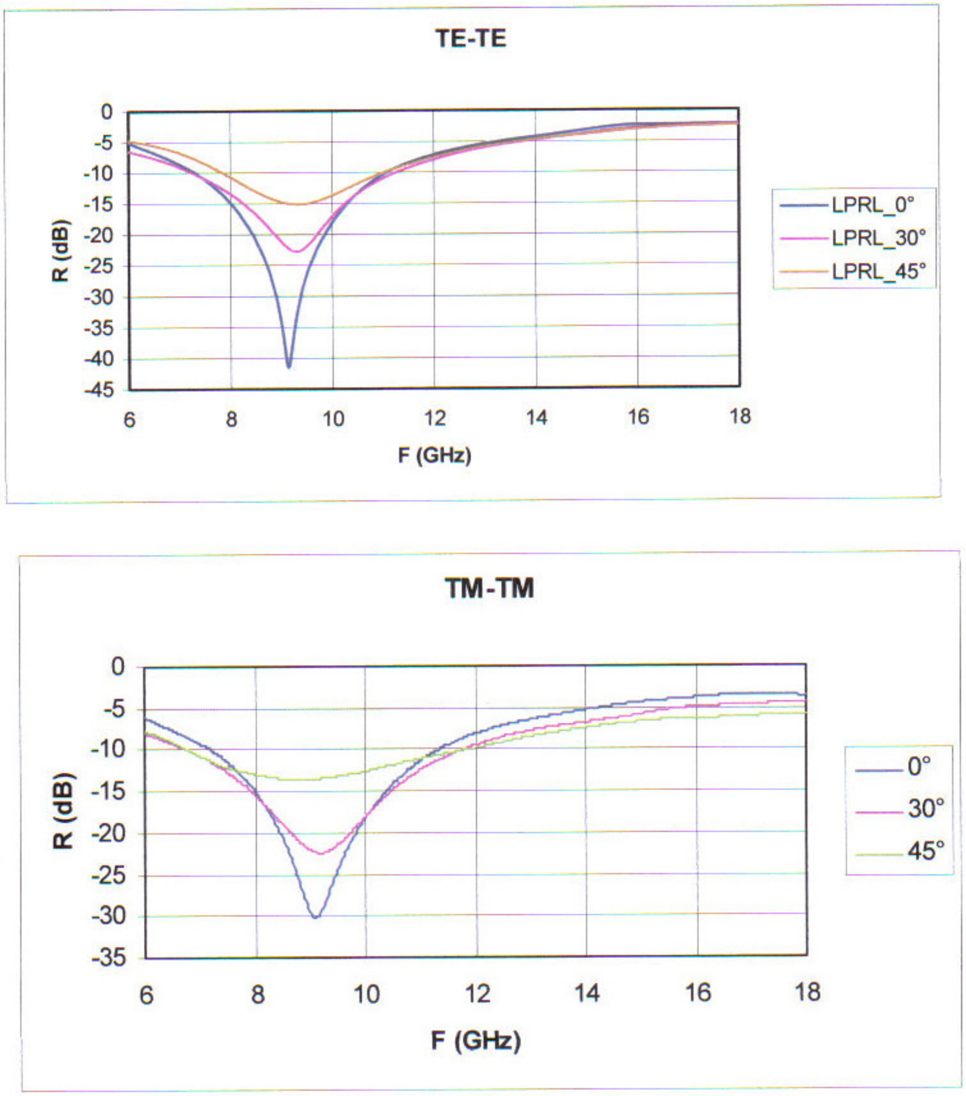

Figure 10: Reflection at different angles of incidence for a 1.9 mm thick LPRL multipurpose coating. The top panel shows the results for TE-TE polarization, the bottom panel for TM-TM polarization.

We note that although LPRL has developed RAM coatings, our core competency is IR stealth coatings, and tuning these coatings for RAM compatibility or to meet other mission-specific requirements. Therefore, our primary thrust in this field is to exploit our IR stealth technology in partnership with current manufacturers of RAM coatings to develop multifunction coatings.

Laser Range-Finder Counter Measures

Laser range-finders are used in targeting systems that threaten both mobile units and infrastructure. The Nd-YAG laser, operating at 1064 nm, is the laser most commonly used in laser range-finders.

LPRL uses its patented light-cascade technology in countering this threat. Figure 11 shows a schematic representation of the light-cascade concept. For a given application, moleulce A is selected to have an absorption band in the region of interest (e.g. 1.064 mm for laser range-finders). Molecule B has an absorption band that overlaps the red-shifted emission band of molecule A, and in turn re-emits at a higher wavelength. This process continues until the final radiation emitted is in a desired wavelength range. The result is a significant reduction in the reflection of incident radiation.

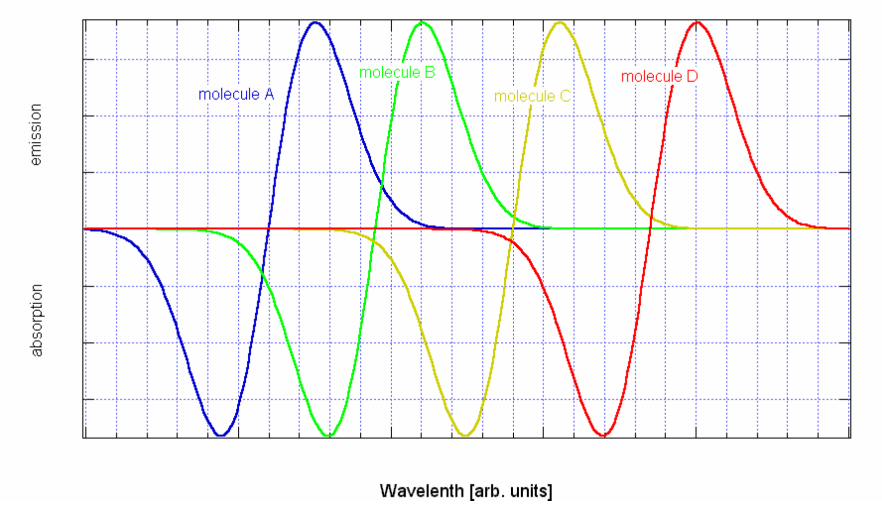

Figure 11: Schematic description of light cascade concept.

LPRL has produced a coating that reduces the effective range of Nd-YAG laser range-finders by almost an order of magnitude. The product is in the stage of laboratory testing and is the subject of a recent patent application.

Below we present data representing the reflection coefficient of three LPRL coatings of different visual colors: brown, sand, and green. The sand and green colors are required to have a relatively high reflectivity in the near IR in order to satisfy NATO specifications, but the brown color is not. The brown coating is therefore doped reduce the reflectivity in the near IR, with the results shown in Figure 13.

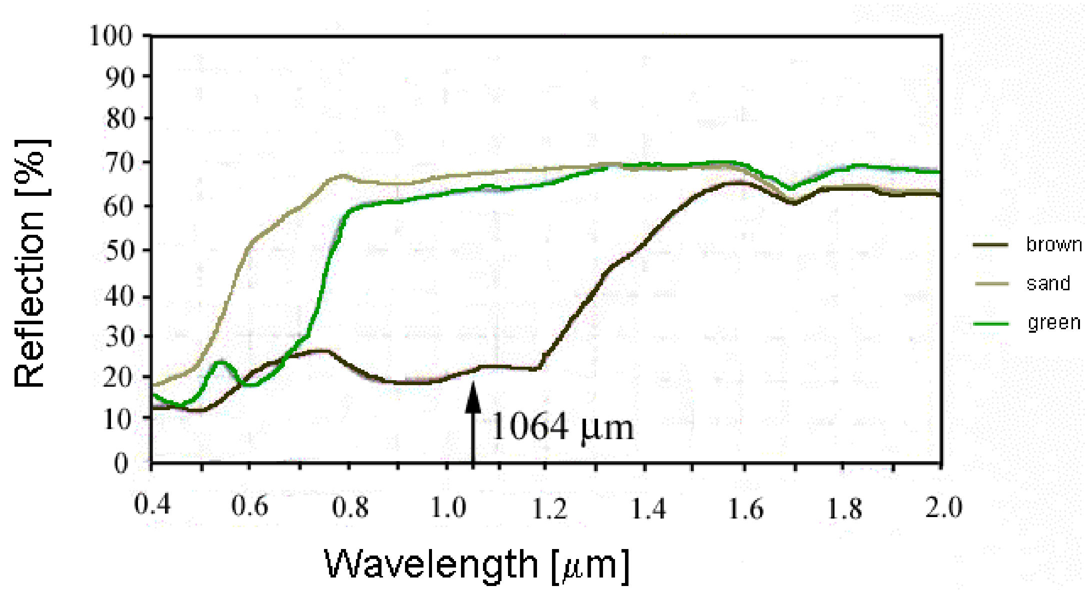

Figure 12: Reflection coefficient of three LPRL coatings with different visual colors.

Recent tests conducted by the DGA have confirmed the potential of the LPRL coatings for countering laser range-finders. Using a military laser range-finder (model TM18), they find that the effective range of the range-finder is reduced by a factor of 5.6 to 9, depending on the angle of incidence between the laser beam and the target.

Conclusions

The modern battlefield presents numerous threats that exploit technology involving IR radiation, including laser range-finders, missile guidance systems and thermal cameras. LPRL coatings are designed to counter these threats. In particular, LPRL have developed low observable coatings that:

1) modify the infrared signature in Bands II and III of hot surfaces on aircraft, vehicles, and military infrastructures (*without* alter RAM properties) in such a way as to deceive thermal imagers,

2) reduce the emissivity of their host in Bands II and III,

3) may be combined with RAM coatings to achieve dual-mode RAM and IR stealth coatings,

4) significantly decrease the maximum range of laser range-finders.

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