Fibre-Optical Light Scattering Technology in Polar Bear Hair: A Re-Evaluation and New Results

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Abstract: In very early studies, the function of the transparent hair of polar bears with their light scattering hollow core has been associated with fibre-optical properties. Critics, arguing that the distance propagated by the light is too short, later denied this. New spectroscopic, microscopic, and laser-optical studies explain the contradiction. The light harvesting mechanism can only be understood as a synergetic cooperation of many of the animal`s hairs. Light is coupled into the hair`s fibre via a scattering process for a short distance where soon after it is coupled out by a subsequent scattering process, just to be coupled again into a neighbouring hair and so on until the light is dissipated into heat or absorbed by the bear`s black skin. In the meanwhile, a small percentage of the incident light is backward scattered. As a result, the pelt`s transparent hairs appear white, while absorbing most of the incident radiation. Moreover, the solar optical technology includes a complementary strategy: the IR -radiation of body`s heat, between 8000 and 12000 nm, is effectively trapped by an analogue mechanism. This is supported by the high absorptive capacity of the fur and the absence of any significant spectroscopic feature in the entire spectral region. The polar bear evolved an efficient optical nano-technology for energy harvesting and energy conservation. Challenges for a biomimetic energy technology based on Mie scattering are discussed.

Keywords: Bionics and Biomimetics, Fibre Optics, Mie Scattering, Polar Bear Fur, Solar Radiation Harvesting, Thermal Insulation.

1. INTRODUCTION

The fact that UV light is poorly reflected from a polar bear fur goes back to studies conducted by Lavigne and Oritsland [1], and Grojean *et al*. [2] and served to explain this phenomenon on the basis of a fibre-optical conduction of UV light to the black skin of the polar bear. Later, Tributsch *et al*. [3] observed that UV light transfer within the transparent hair is highly attenuated. They explained the function of the polar fur as a transparent insulation with scattering processes, coupling light into the hairs, but also pointed out to a complementary mechanism: the generation of *keratin* luminescence and the conduction and collection of it. In several papers [4-6], D.W. Koon criticised the popular scientific interpretations of these studies concentrating mainly on the supposed fibre-optical properties of polar bear hair. D.W. Koon and other scientists [7] specifically argued that light concentration from solar light into polar bear hair acting as fibre optical devices would not work because entropy would have to be drastically reduced. They claim that this is forbidden for thermodynamic reasons. This seems to be a serious argument, but we do not agree for the following reasons: The light transmitting polar bear hairs act is subject to non-imaging optics. This discipline of optics, which was essentially developed by M. Ploke [8], R. Winston [9] and J. O'Gallagher [10] aims at pure light concentration, which is more effective than imaging optics, which can also deal with images. Non imaging optics mostly use light`s deflection, refraction and scattering in special geometries [11]. Non imaging optics is now applied in a wide range of fields, ranging from solar light collection with Winston collectors to modern thin layer solar cells, where the non-imaging optics is integrated via light scattering structures. What is the expected limit of light concentration? The obtainable light concentration is given by [12]:

$$C = A\frac{n^2}{\sin\theta} \tag{1}$$

where A is a proportionality factor, n is the refractive index, and Θ is the light incidence angle. The proportionality factor A depends on the geometry of the light collecting system and can reach values up to 4. With a non-imaging optical light concentrator based on a Winston collector made of sapphire (high refractive index of n = 1.76) a world record solar light concentration of 84.000 times was obtained [12]. A higher light concentration was obtained than the concentration of light emitted from the sun surface (64.000 times concentration needed). This is, in this case, not a contradiction with thermodynamics because light was concentrated within a sapphire utilizing its high refractive index.

How does this match with the entropy and thermodynamics argument advanced by critics

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Reversible thermodynamic arguments, which are apparently used, do not apply here, for the reason that the non-imaging collectors are not closed, but open systems, where the energy (light) is passing through. If the system is assumed to be larger, to include heat generation, then also no entropy problems arise, since heat production from light means strong entropy generation.

Koon also argued that there are no convincing evidences for a fibre-optical mechanism in polar bear hairs, since the hairs are absorbing and attenuating light too strongly. Other authors appear to join this opinion [7,13]; Koon, however, conducted his studies investigating individual hairs of polar bears and the relatively short distance the visible light can travel within the hair (high attenuation of 2-8 dB/mm). In his experiments, light was coupled axially and perpendicularly into an individual hair [6], studying the attenuation along the hair. The experiments revealed that the polar bear hairs attenuate the light significantly with only a very small percentage of the visible light traveling to the end of the studied strand of hair (2.5-4 cm). Koon then concluded that no measureable amount of UV (ultra violet) and visible light would reach the skin of the polar bear (traveling 5-15 cm), due to the very high attenuation. However, the polar bear pelt`s light collecting is not acting via individual hairs, but via their synergetic action. Therefore, the study presented here is re-examining the problem and approaching it as a collective mechanism of the animal`s overall fur, basing it on the following description from the literature [3]: The polar bear´s fur combines two distinctive optical phenomena: the light collection through optical scattering and the luminescence light collection with the aim of capturing light and concentrating it at the basis of the hairs, where it is converted to heat. The transfer of the light is facilitated by the combination of those two optical phenomena. Nevertheless, the light collecting mechanism`s thermal energy gain is moderate and contributes to the overall heating of the animal weakly, hence the mechanism implemented is considered evolutionarily young.

It is worth mentioning, that in a previous study [3] samples of different white animals' hairs have been examined to investigate the morphological differences. Polar bear hairs showed a peculiar, geometrical tubular structure of the core with statistically distributed scattering centres. This hollow hair core is characteristic for several animals living in cold climate, like reindeer, wolf, or alpaca and has itself been discussed as a component relevant for the improved insulation of the polar bear pelt [14]. Interestingly, the same study [3] found that the luminescence of the polar bear hairs is characteristically different from that of the white hair of other investigated mammals. The onset of the luminescence is shifted to longer wavelengths producing a characteristically larger luminescence gap between absorption and luminescence, and the luminescence band is also spectrally broader and more intensive. This indicates that some evolutionary adaptation occurred in the direction of luminescent light collection.

The Polar bear has a bulky fur, consisting of two well-defined layers: a softer layer of dense white under-fur topped by an outer layer of 5-15cm long guard hairs [13]. The guard hairs layer comprises the majority of the total animal`s fur depth, and has a lower radiation interception function (the probability per unit coat depth that a ray will be intercepted by a hair (m^{-1})) compared to the highly-dense under-fur layer (see later Figures **13** and **14**). Consequently, the guard hairs layer permits the forward-scattering of radiation into the lower layers of the fur above the black skin, where the emitted thermal radiation of the body is trapped (continuously absorbed and re-emitted) in the lower layer of the fur due to the under-fur layer`s higher radiation interception function. At the boundary between the fur`s two layers, the forward-scattered radiation through the guard hairs towards the lower regions of the fur would more likely be intercepted by hairs due to the high density of the pelt in the under-fur layer. The intercepted radiation is re-scattered, converted to heat, and eventually absorbed by the black skin of the animal. Therefore, the fur provides the animal with an excellent thermal insulation to help maintain an approximately constant body temperature and metabolic rate even when the ambient temperature is around –50 °C [15].

To avoid overheating and dangerous hyperthermia during summertime and predation, the polar bear is equipped with adaptations to cope with the excessive heat. According to Orisland and Scholander [3], the polar bear´s pelt supports efficient heat conduction, when wet. The animal takes advantage of it by swimming a lot in order to cool down in summer, and to warm up in the winter when the ice-free water is warmer than the freezing land´s temperature or wind chill [14]. In addition to such adaptations, the polar bear has a pair of 2 mm thick sheets of striated muscles only 0.5-3 mm under the skin, rich in blood vessels. These sheets are working as a heat dissipation device [3].

And the polar bear regulates heat dissipation also through its sub-dermal vasomotor controls, whereby the blood vessels are contracted or dilated [3].

2. MATERIALS AND METHOD

The optical and morphological properties of animal`s fur were examined to provide an explanation of the fur`s adaptations. Samples of an adult Polar bear`s hairs, collected in a non-invasive manner, were donated by the Wilhelma Zoo, Stuttgart. The samples were examined at the ITV Denkendorf/Stuttgart University and later at the laboratories of the Physical Chemistry department at the University of Vienna.

Figure 1: Polar Bears at the Wilhelm Zoo, Stuttgart/Germany [16], where the hair samples were obtained from.

2.1. Spectroscopic Measurements

To fully understand the optical and thermal adaptations of the polar bear fur, two different important spectral regions have been investigated: the VIS (visible) and NIR (near infrared) bands and the MIR (middle infrared) band. Two different types of samples were used. The first type is a thin/single layer hair sample of the polar bear hairs (Figure **2a**) with a single layer of the hairs bundled together. The other type is a thick sample of the polar bear hairs (Figures **2b** and **c**), with multilayers of the hairs bundled together.

2.1.1. VIS-NIR Range

Two different sets of measurements were conducted using the two different types of samples in order to characterize the optical properties of polar bear hairs in the VIS and NIR bands. First, the transmittance and reflectance spectra of a thin/single layer sample of hairs were measured using the VERTREX 80 spectrometer at the laboratories of ITV Denkendorf, equipped with an integrating sphere. Tufts of several hairs were bundled together and arranged in front of the integrating sphere with the axis of the hairs perpendicular to the arriving light beam, creating a plane of hairs mostly oriented in one direction. The sample consisted of one layer of hairs (Figure **2a**), to reduce the effective absorption and to accurately measure individual hair`s transmittance and reflection properties. The reflection measurements were conducted using a golden disc, with the hairs attached on the backside of the integrating sphere and illuminated through a small opening. The main opening of the integrated sphere is closed with a flat golden disc having the same surface coating as of the inside.

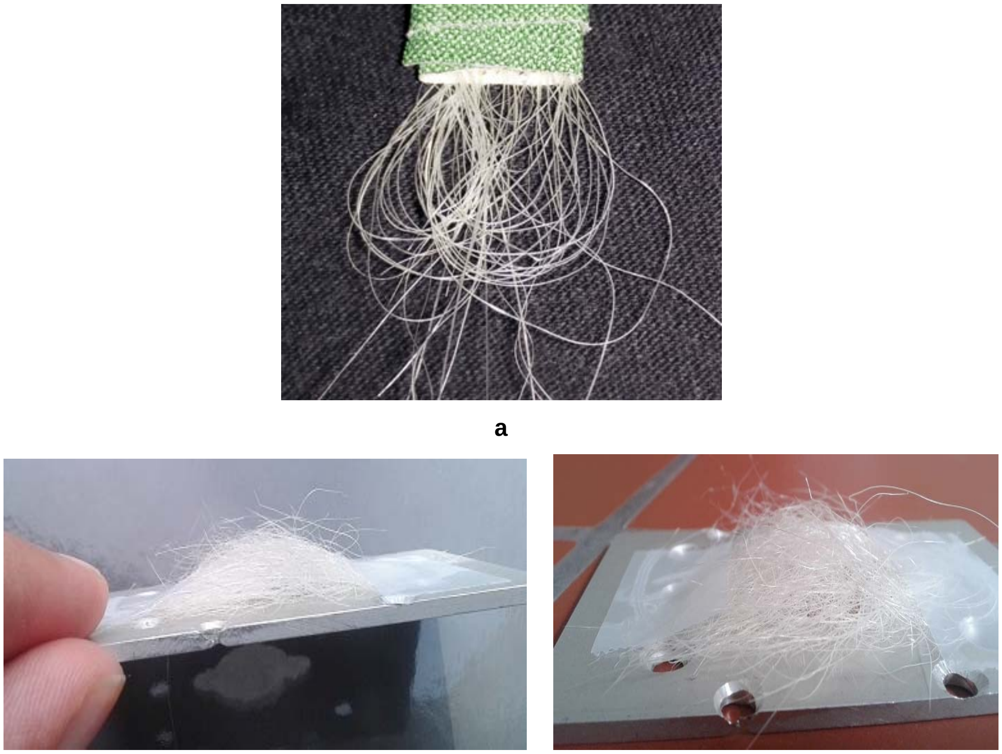
The transmission measurements were conducted using a similar method, except that the bundle of hair was placed across an open aperture. Then the forward-scattered light was collected by the integrating sphere, where the transmission spectra were measured. The absorption spectra were later calculated using *Kirchhoff*'s law of radiation

Second, for a better understanding of the overall optical properties of the animal`s fur, and to confirm earlier measurements, the absorption was measured at the laboratories of the Department of Physical Chemistry in the University of Vienna. The sample of hairs was placed in the spectrometer`s probe holder, creating a plane of hairs that were mostly oriented in one direction. The Sample consisted of multi-layers of hairs to roughly simulate the structure of the polar bear fur (Figures **2b** and **c**).

2.1.2. MIR Range

In order to understand the adaptations of the Polar Bear fur in the thermal radiation band (MIR), the sample with multi-layers of hairs was used. The transmittance and reflectance (diffuse + specular) spectra of the hairs were measured using the VERTREX 70 spectrometer at the laboratories of the Physical Chemistry department in the University of Vienna. The sample of hairs was placed in the spectrometer probe holder, creating a plane of hairs that were mostly oriented in one direction (Figures **2b** and **c**). The reflectivity and transmissivity were measured, and the resulting absorptivity was calculated. The thermal radiation range of the animal was examined and the hairs spectral properties plotted at wavelengths between 8000-12000 nm.

The same procedures were followed for the measurements of the optical properties in the MIR



a

b **c**

Figure 2: Mounting of polar bear hair for spectroscopic measurements. (**a**) A sample with a single layer of hairs. (**b** and **c**) A sample with multilayers of hairs.

band using the sample of single layer of polar bear hairs.

2.2. Microscopic Measurements

The morphological properties of hairs were examined using two types of observational tools at the ITV Denkendorf Laboratories: the Optical Microscope (OM) and Scanning Electron Microscope (SEM). The sample for the OM measurement consisted of several hairs placed over the microscope`s slide glass, creating a plane of hairs. The SEM sample of hairs was embedded in the centre of a wool fibre bundle and then sliced by a slicing tool to produce a cross section of the sample on a flat probe holder.

2.3. Laser Experiments

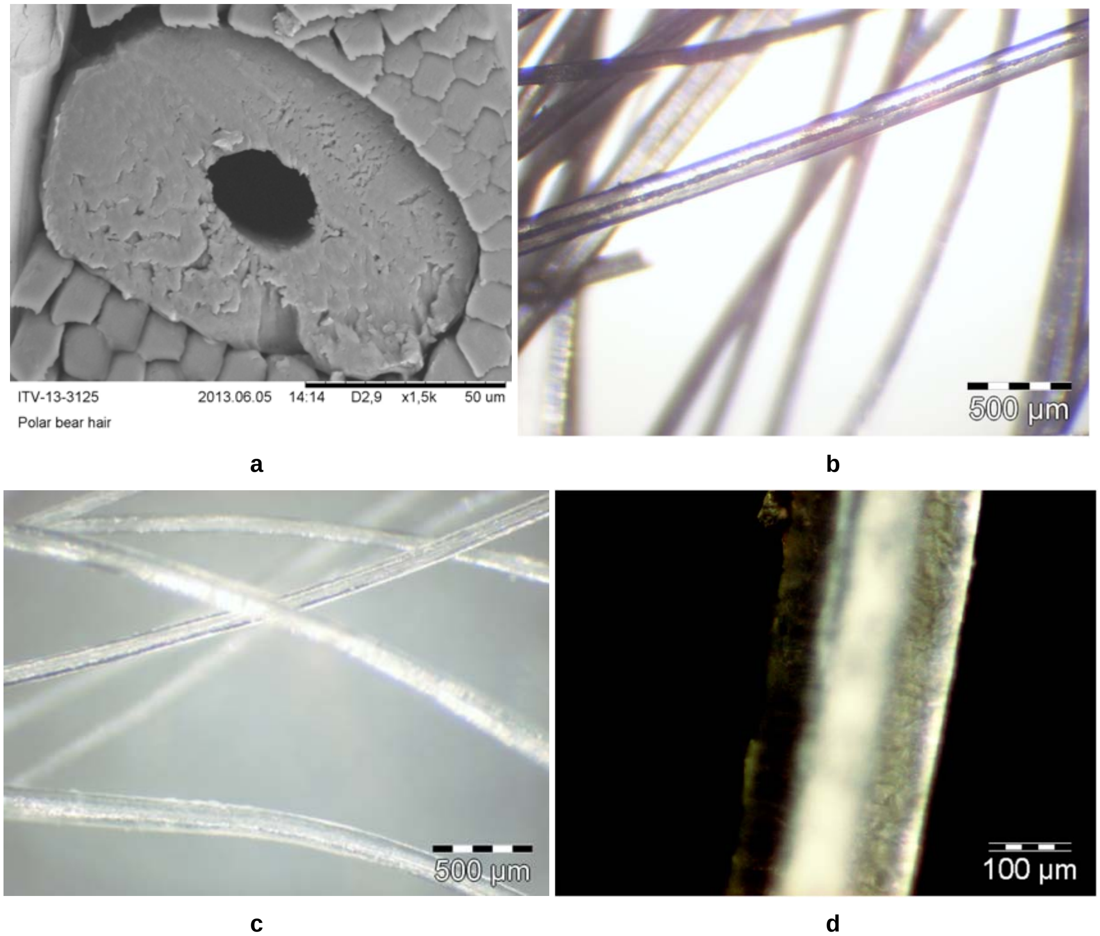
To investigate the scattering phenomena of the hairs, a bundle of the polar bear´s hairs was illuminated with a 401 nm and a 532 nm laser pointer pen (~ 1 mW); using a mirror in order to demonstrate the cross section area of the laser beam.

3. RESULTS AND DISCUSSION

Figure **3a** shows a cross sectional SEM image of the polar bear`s hair, with a diameter of approximately 100 - 150 μm; it was embedded in a wool fibre bundle. The hair has a central large hollow core that occupies about one third of the total width of the hair shaft. The hairs are translucent for light (Figures **3b** and **c**), due to the fact that pure *keratin* is practically transparent for visible and near infrared light. The hairs are entirely transparent from 300 to 2600 nm (reproduced in Figure **6a**), since *melanin* is absent in polar bear hair. In Figure **3b** the light scattering core is seen as a dark line in the centre of the hair shaft, due to the fact that light arriving from the back is scattered away. In Figure **3d** the illumination is different in larger magnification, where one can see the light scattered from the scattering centres within the hollow core, producing the white central stripe.

Since the hair is basically entirely transparent, it`s scattering properties for light for the entire VIS spectrum must be responsible for the white or very light yellow optical appearance of the animal`s fur; that's why the black skin of polar bears is not visible when looking at the fundamentally-transparent pelt, see Figure **4**.

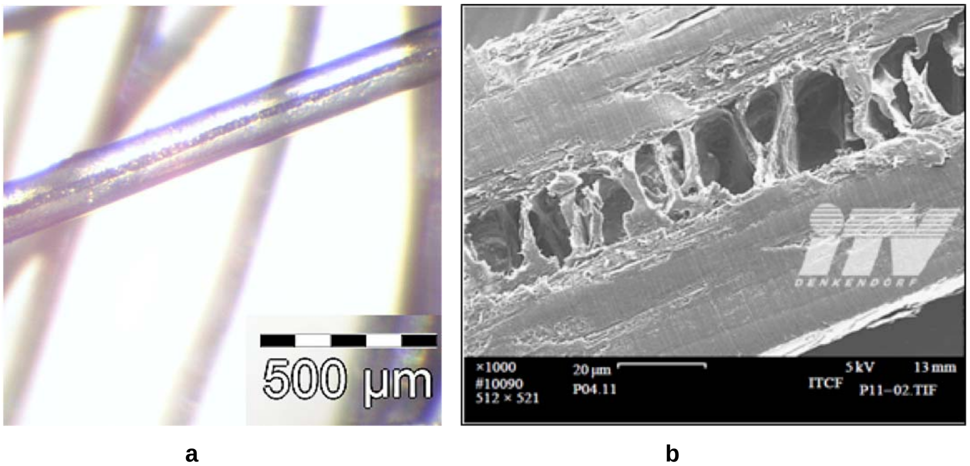
The extraordinary scattering properties of polar bear hair can also be demonstrated with the help of a 2-3 mm broad laser beams. The incident laser beam on a



a b

c d

Figure 3: Microscopic studies of polar bear hairs. (**a**) A cross sectional SEM image of the polar bear`s hair, embedded in wool fibers. (**b**,**c**,**d**) Optical microscopy images of hairs at different magnification rate.



a b

Figure 4: (**a**) A zoomed-in image of Figure **3b**: the central hair channel seen in transmitted light in an optical microscope. (**b**) A cross section in a SEM image [17]. The quite smooth geometric structure of hair and medulla, the interior channel, is recognized as well as the ability of scattering centres to redirect light (left). The dimension of scattering centres is 3 -20 µm.

tuft of polar bear hair produces a widely dispersed and channelled light. The ratio of cross sections between the incident light and the illuminated light tuft can be seen in Figure **5a**, where the cross section of the laser beam is seen when reflected from a mirror below. The aim of the experiment was to show how a small pointed green laser beam is significantly scattered from the polar bear`s hairs. It produces a relatively significant optical re-disturbing of the light, and light guided through the hair, even though for a shorter distance.

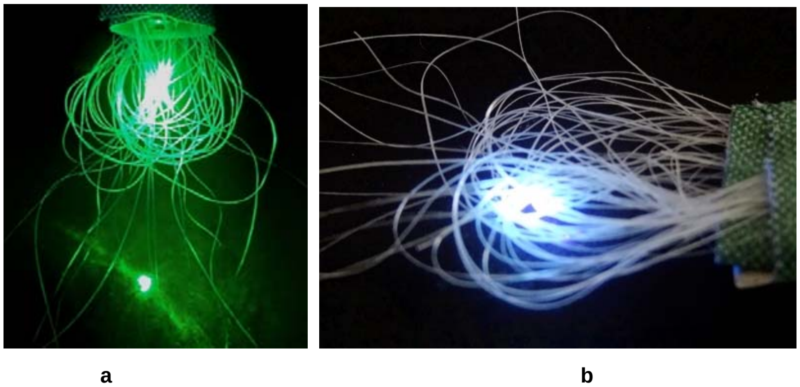


Figure 5: A narrow 2-3 mm laser beam of 1mW (seen in image (**a**) as a spot when reflected from a mirror) generates a lot of scattered light and light coupled into the hair shafts in a tuft of polar bear hair at (**a**) 532 nm and (**b**) 401 nm wavelengths.

Prior to examining the optical properties of the polar bear`s hairs it is important to have a look at the optical studies of the animal`s individual hair and the hair`s material, *keratin*. Those studies were published in the literature [18,19] and are here reproduced in a simplified way in Figure **6** (data transformed into a new graph from [19,20]). It can be seen in the left graph that up to 2600 nm, *keratin* is entirely transparent. Pronounced absorption peaks arise only near 3000 nm and 7000 nm as shown in Figure **6b**. In the absence of scattering processes, the polar bear pelt would consequently be transparent for the visible light and an observer should be able to see the black skin of the bear. However, this is not the case (see Figure **1**). The relevancy of light scattering processes is seen in Figure **7**, where the absorption of tufts of polar bear hair is reproduced in the visible and near infrared region. The magnitude of light absorption, of course, depends on the thickness and density of hair tufts. Here it is seen that already a relatively thin and loose tuft (Figures **2a** and **c**) "absorbs" 60 to 80 % of the incident light. This light is, of course, not directly absorbed, but scattered, deviated and finally quenched by some complex intrinsic deactivation processes. If a thinner layer of

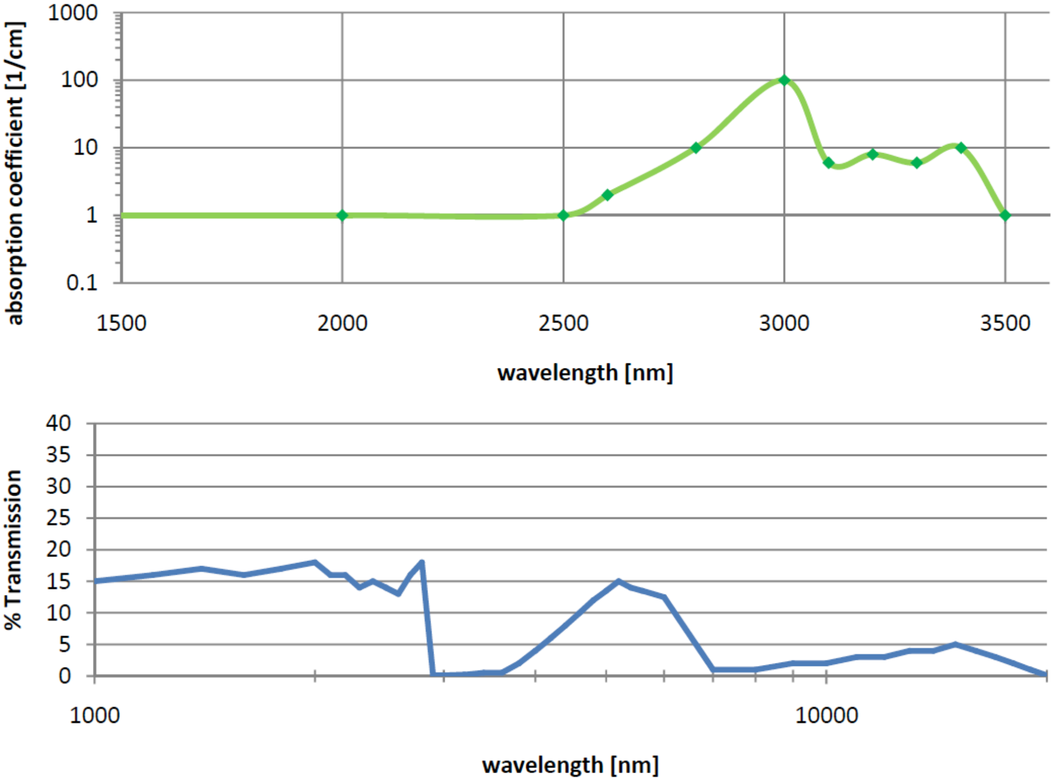


Figure 6: (**a**) Keratin absorption spectrum in the visible and near infrared is shown simplified (modified from the literature [20]). (**b**) The transmission spectrum for an individual hair of polar bear [19].

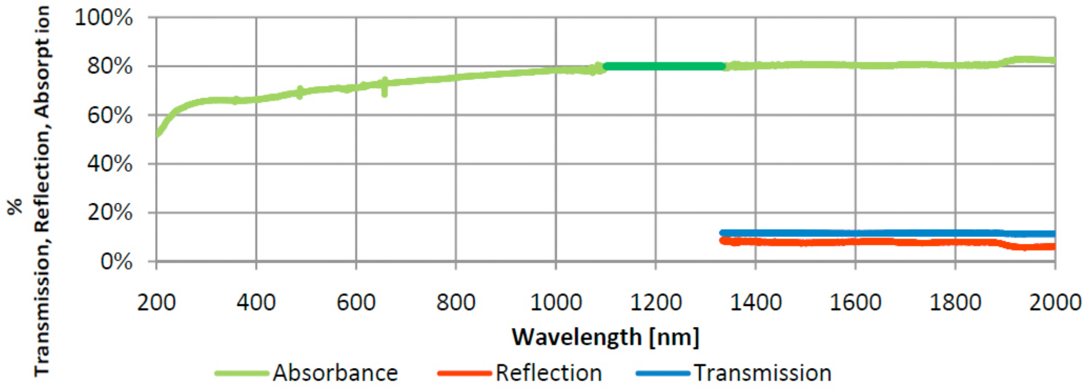


Figure 7: Spectroscopic measurements of polar bear hairs tufts in the UV-VIS-NIR bands; indicating strong “absorption" of light via scattering processes. The absorption spectrum was obtained from fitting of two separate measurements of the same polar hair sample (multi-layers hair sample).

hair is measured (Figures **2a** and **5**), which permits the transmission of 60 to 90 % of incident light, much smaller “absorption” is seen (Figure **8**).

In spite of the transparency of polar bear hair`s keratin, the visible and near infrared light is strongly absorbed by polar bear hairs due to the scattering processes. Evidently, with a thin/single layer tuft of hair, more VIS and NIR light transmitted. It is important to note, and it is confirmed by the measurement of Figure **7**, that the effect of scattering is quite uniform in the entire visible-infrared range, because of the special properties of Mie scattering (this will be discussed later).

Depending on the thickness of polar bear hairs tufts, measurement of the optical properties of the polar bear`s fur further in the infrared region, yield, of course different magnitudes for absorption, transmission and reflection. Figures **9** and **10** compare the optical properties of thin/single layer and thick/multi-layers hair samples respectively, in the thermal radiation region between 8000 and 12000 nm. Here in this spectral region the thermal emission from the body of the polar bear, according to the Planck law, is expected. The high absorptivity and the lack of characteristic structures, up to very long wavelengths, support the dominance of scattering processes in producing these optical properties.

The generated two plots, Figures **9** and **10**, show high absorptivity in this wavelength range with a reasonable thick pelt, and this is very important in terms of thermal insulation, since the black skin of the polar bear is emitting thermal radiation in the region between 8000 and 12000 nm. This radiation is scattered by the scattering centres within the hair core and confined within the hair`s shaft. Then it is scattered again, leaving the hair another time just to be re-confined and re-scattered again and so on, trapping the heat within the pelt. This way the fur is significantly minimizing the radiation losses from a polar bear´s body in the cold environments by effectively scattering and trapping the long wave radiations. Hence, it is not

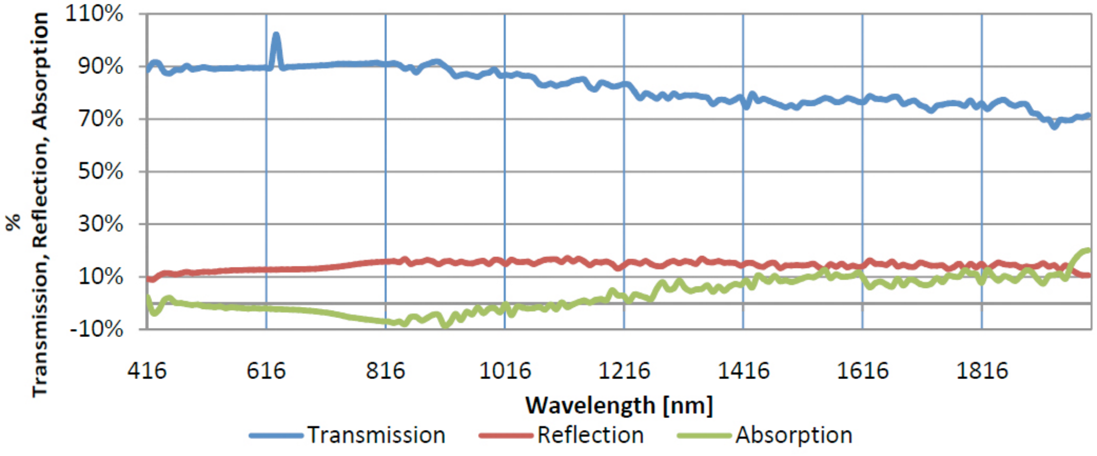


Figure 8: Optical properties of polar bear`s thin/single layer tuft of hairs, measured with an integrating sphere.

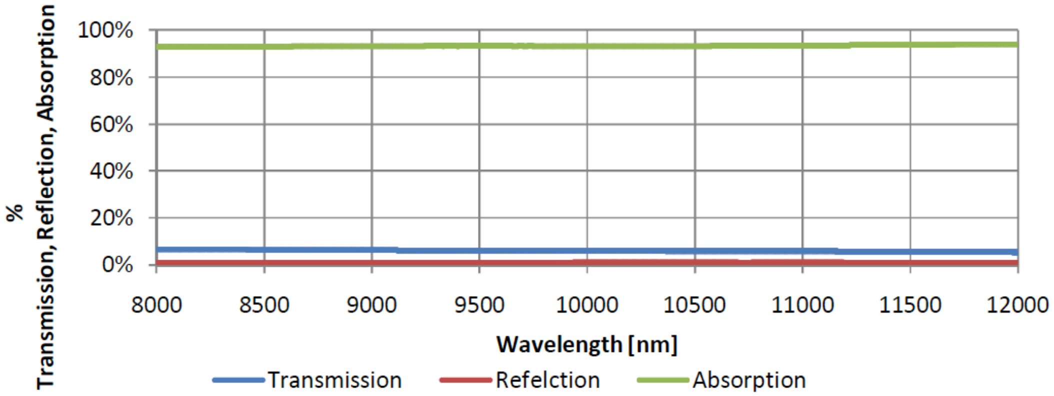


Figure 9: The absorption properties of tufts of polar bear hairs in the far infrared for thick/multi-layers hair sample.

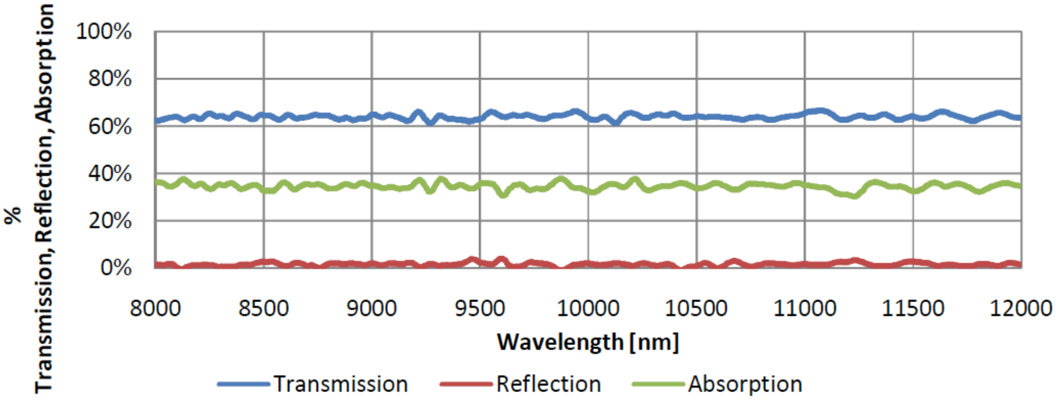


Figure 10: The absorption properties of tufts of polar bear hairs in the far infrared for a thinr/single-layer hair sample.

possible for IR-thermography to detect the polar bear easily, except for the animal`s nose and eyes.

The optical behaviour of the polar bear hairs up to 27000 nm is shown in Figure **11**, demonstrating the high absorptive capacity of the fur and the absence of significant spectroscopic feature in the entire spectral region. The “absorption” remains constant within 15%. In the region of 2000 to 6500 nm small absorption patterns are seen, which are due to *keratin*, as seen in Figure **6a**. This optical absorption by *keratin* obviously plays only a minor role in avoiding radiation loss.

This behaviour of the polar bear pelt in the far infrared region could be confirmed via a transmission measurement (Figure **12**). The transmission was very low, because of a thick/multi-layers sample, but still showed a contribution of the keratin absorption bands between 2000 and 6500 nm.

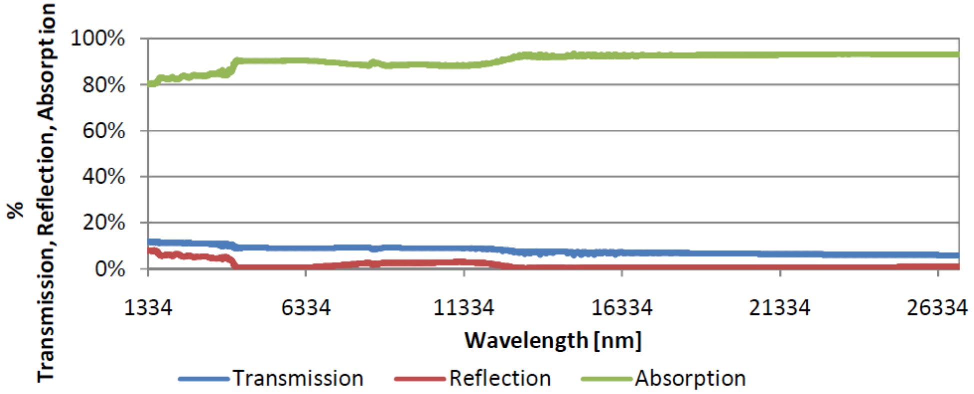


Figure 11: Optical spectra of a tuft of polar bear hair measured until 27000 nm.

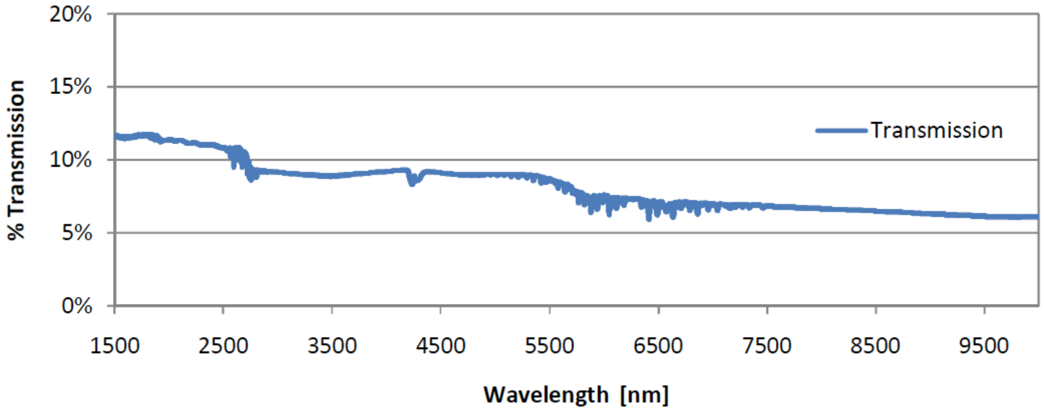


Figure 12: Transmission of tuft of polar hair measured in the infrared. The absorption peaks characteristic for keratin 2100 and 6500 nm are visible, like in Figure **6**.

4. DISCUSSION

From the absorption behaviour of *keratin* (Figure **6**) together with the optical photographs of the polar bear hairs (Figures **3** and **4**), and looking at results from Figures **9-11**, it is clear that optical transmission is rather controlled by the light scattering processes arising from the particles and structures within the medulla of the hair (Figure **4a**), not by the absorption coefficient of the *keratin* material. Thus, the transmission of light is controlled by the thickness and structure of the hair tuft (Figures **8** and **9**), determining it via its scattering properties. This is also to be observed further in the infrared region (Figures **10** and **11**). Remarkably, there are no characteristic spectroscopic structures observed in the homogeneous optical spectrum besides small absorption peaks arising from *keratin*. These absorption peaks of *keratin* which are appearing in the single polar bear`s hair measurement (Figure **6b**) and expected near 3000 and 7000 nm, are supressed, but still visible in Figures **11** and **12**. This testifies for the dominance of the light scattering physical process, which works efficiently in the VIS and NIR, as well as very far into the infrared region. So what kind of scattering process is it?

The optical processes are essentially determined by the scattering in the hair`s medulla. This process couples light into the fibre optical shaft of polar bear hair, along which light is conducted, before being scattered again out of the hair just to be coupled again into the next transparent hair via a subsequent scattering process, see Figure **13**.

When light travels in the hair shaft, the *"scattering"* particles are actually the voids. Mie scattering is proportional to the Fresnel coefficient, which is:

$$\Gamma = \left(\frac{n_s - n_0}{n_s + n_0} \right)^2 \tag{2}$$

where n_s is the refractive index of keratin and n_0 that of the voids. If the scattering of light on the keratin structures would be calculated then the Fresnel coefficient would become zero because the refractive indices would be identical. However, when the scattering centres are considered to be the voids, the scattering process would materialize. The value of the Fresnel coefficient is the same no matter what direction the light is traveling; whether from the material with the high refractive index to the material with the lower one or vice versa. The scattering "particles", for light traveling within the hair, in the medulla of polar bear hair are therefore the voids in the central channel. For light coming from the outside, the scattering particles are *Keratin*, and they are of the order of 3 to 20 µm (compare Figure **4a** and the bright stripe in Figure **3d**); which is larger or comparable to the wavelength of the infrared light used in the optical measurement (0.5 - 26 µm). Therefore, Rayleigh scattering can be excluded; however Mie scattering (mostly spherical shapes) and Tyndall scattering (arbitrary shapes) are applicable. Generally speaking, the scattering is sensitive to the particle`s size, yet quite insensitive to the light`s wavelength if it is larger than the size of scattering particles. This may explain why absorption, reflection and transmission of the examined bundles of hairs are found largely independent of the wavelength. Mie scattering is also responsible for the white appearances of the clouds, where a white colour appears when a broad range of wavelengths is equally scattered via the small water droplets as scattering centres. Hence, the white colour of the polar bear`s fur can be taken as another example of Mie scattering. Mie

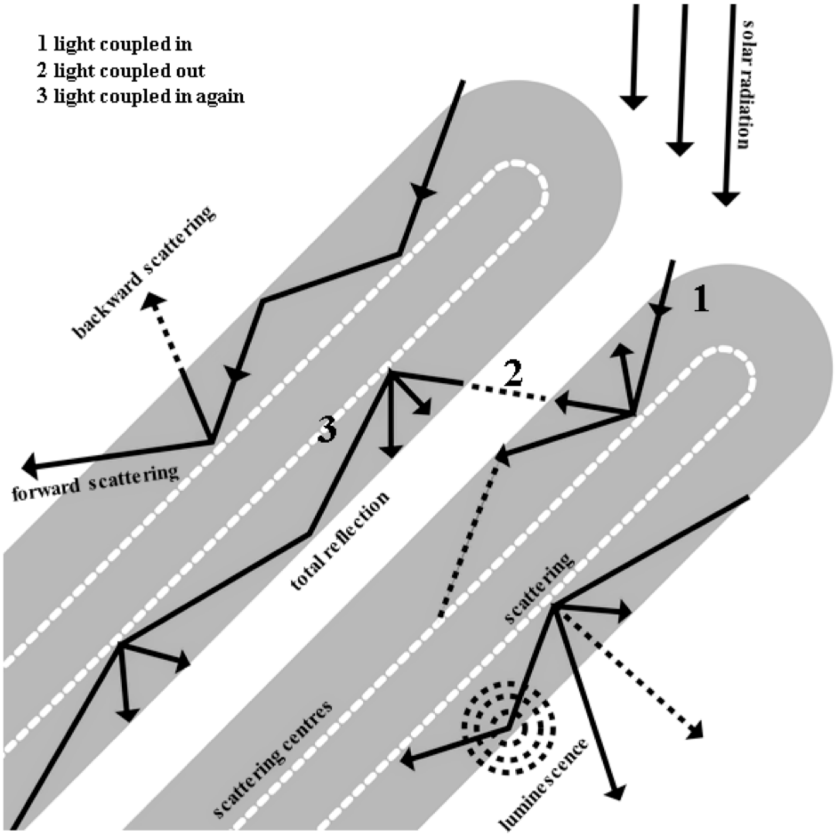


Figure 13: Scheme explaining the synergetic function of the polar bear`s hairs.

scattering is theoretically quite well understood, but requires intensive computation. Recently, approximate formulas have been evaluated and are applied to understand scattering processes in FTIR microscopy of biological samples [21].

Another advantage for the white colour of the fur [22]: a study conducted by Walsberg *et al*. on pigeons, suggested that the heat gain of black plumages exposed to simulated solar radiation is much greater than that of white plumages when wind velocities are low. However, because radiation penetrates deeply into white plumages, heat generated by irradiation is substantially insulated from loss to the environment, and radiative heating of these plumages is less dependent on wind speed than that of black plumages. Thus, the radiative heat loads of black and white coats rapidly converge as wind speed increases.

What are the advantages of having such a light-scattering based optically active pelt for the polar bear? All together the light collecting phenomenon is subject to non-imaging optics. The light concentration is dependent on the refractive index of hair`s *keratin*, as well as on the geometry of light capturing, described by a light collection angle and a geometrical factor *A*, as explained earlier in relation (1). The animal`s hairs have the physics and the properties of optical fibres. They are transparent and have a refractive index of n = 1.56. For comparison, Crown glass has a refractive index of n = 1.52, and Flint glass of n = 1.62.

As demonstrated in Figures **13** and **14**, when scattering processes occur in the central hollow core, light is definitively coupled in and travels along the hair`s fibre. Soon, a new scattering process will occur and light will be coupled out of the hair`s fibre. However, within the pelt`s structure this light will again be coupled in into the next hair to be coupled out later and so on. That way light is captured until it is dissipated into heat within the pelt or absorbed and converted to heat by the black skin of the animal. It is interesting now to return to the argument raised by Koon [4–6], who criticised, that radiation is not propagating a longer distance within individual hairs to reach the black skin. If nature actually would have allowed that by limiting the scattering possibilities, the polar bears black skin would be shimmering through the pelt. This would have been a big disadvantage for hunting. The polar bear consequently developed hair with strong light scattering properties, and relied on a cooperative action of many hairs in the harvest of individual photons.

Parallel to the light capturing process via light scattering, part of light`s energy will also be converted to *keratin* luminescence, which will equally be collected and converted into heat [3]. A small fraction of the light, originating from all wavelengths, will be scattering backward from the animal`s pelt, generating the white appearance of polar bears. Additionally, the air cavities within the hairs provide an effective thermal insulation (Figure **4a**).

However, the main advantage of such an insulating pelt, based on scattering of electromagnetic radiation, can be found in the infrared region between 8000 and 12000 nm. In this region, the polar bear will emit the body`s heat radiation according to Planck`s law. Interestingly, the polar bear pelt exhibits a perfect absorption of this radiation from the bear's body as shown in Figures **9** and **12**. Therefore the animal is taking advantage of a perfect greenhouse climate above his black skin; wherein the heat radiation, energetically mostly arising from the animal's feeding habits, will be trapped and will maintain the inner pelt at elevated temperature, as the schematic drawings of Figures **13** and **14** show.

4.1. Opportunities for Biomimetic Energy Technology

Based on the knowledge gained through this study it is possible to discuss the technical benefits of the polar bear fur in the following way: The pelt consists of light transparent *keratin*, containing no pigments but providing scattering centres via the hollow, structured cores of the hairs. This gives the pelt the advantage to appear white as a result of the back-scattering of visible light of all frequencies without suffering the problem of photo-degradation. Light is not generating chemical radicals, through photochemical reactions, but is simply scattered without dissipating energy.

Due to the absence of light-absorbing pigments another phenomenon must be responsible for light capturing. As explained above it is the ability of hairs to couple light into the transparent fibre optical hair shaft via scattering processes. In spite of the short distance

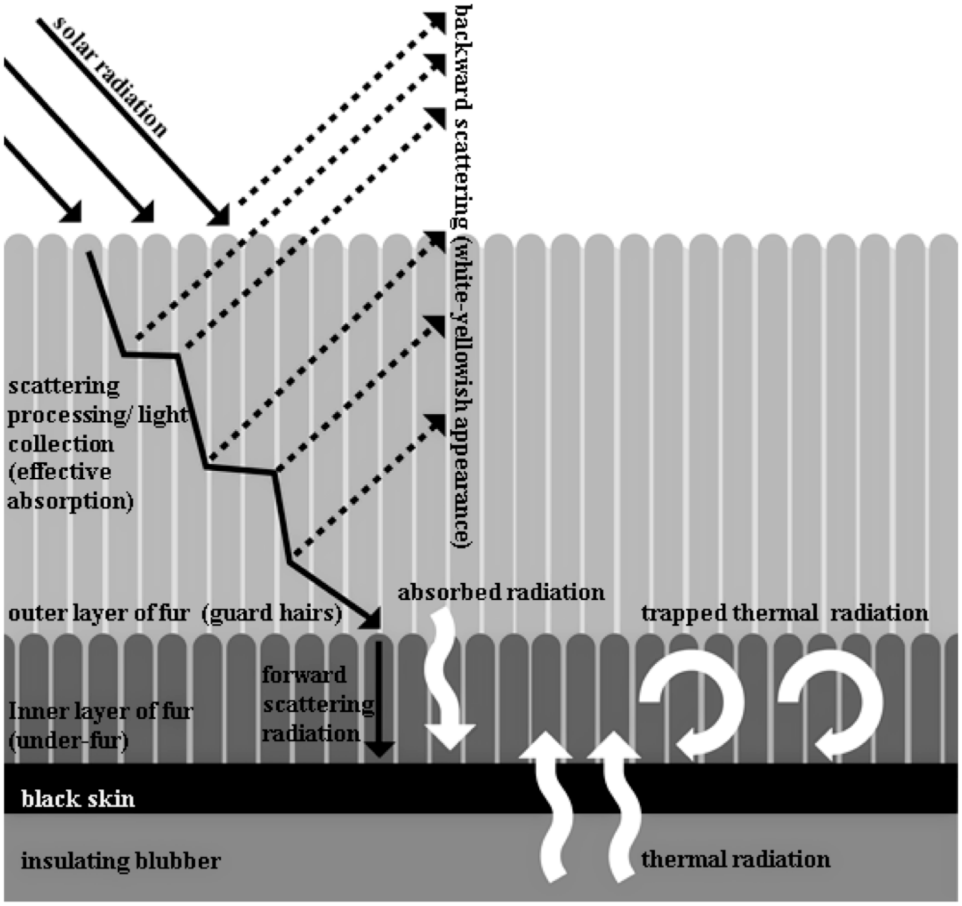


Figure 14: Diagram explaining the energetic function of the polar bear`s pelt.

the coupled-in/captured light propagates within the transparent hairs, photon capturing in the pelt works well because of the synergetic cooperation of many hairs within the animal`s fur. Photon energy is handled from one hair to another and so on. In this way the solar radiation energy reaches the black skin or is dissipated within the highly-dense lower layers of the pelt, maintaining a micro-climate above the skin and lowering the loss of heat from the skin to the environment via convection and conduction. As a result, the pelt works like a transparent insulation material. The polar bear fur`s adaptation continues to the MIR range, where the fur is also efficiently retaining and trapping the infrared radiation emitted from the polar bear body at 8000-12000 nm. The trapping of the thermal radiation does not depend on selective molecular-spectroscopic processes, but is rather provided in a wide range of frequencies because of Mie scattering, which is fairly independent of light frequency. This gives the polar bear a significant advantage, since the trapped thermal radiation energy cannot any more escape and dissipate to the surroundings, keeping the animal warm. Such a property of a wide frequencies barrier against radiation energy loss is quite special and interesting, and it deserves biomimetic consideration. Mimicking the functionality of the Mie scattering process in the polar bear fur is a very attractive technical strategy for two reasons. First, it works both in the visible and near infrared range, where the solar energy of the incident light is concentrated. Second, it works also in the far infrared, where the body`s heat radiation is emitted. Therefore, this process may serve for two purposes, the capture of solar light and the confinement of the body`s heat and thermal radiation.

Most of the solar thermal collector systems in the market suffer from high thermal radiation losses, where the surface temperature of the collectors is reasonably high. The elevated surface temperature of the system negatively affects the system’s integrity and efficiency. In contrast, the polar bear´s fur has evolved for a complete retaining of the thermal radiation within the fur (no IR-photography image can be obtained of the animal; except for the nose and eyes). In contrast, technical thermal heat collectors can be seen in IR images. Thus, biomimetic research is warranted, to deal with the surface`s temperature of the solar thermal collectors.

The technological challenge appears to be relatively clear cut: The interior of thin UV-stable transparent plastic tubes should be filled with scattering particles to mimic the behaviour of hollow polar bear hair. Then different woven pelt structures should be explored to understand the collective behaviour of optical hair fibres. The technical challenge therefore is essentially focused on tailoring artificial prototypes of polar bear hair using appropriate radiation stable plastic material, or, better, artificial keratin since it is already being used for artificial hair. Here, the optimization of scattering centres in the nano and micro range will require some systematic research. It will have to be learned how voids of well-defined size distribution within the keratin or plastic material can be produced. Radiation scattering plastic hairs could be arranged in fur-like mats to cover the facades of buildings with a structure similar to the structure of the polar bear, serving for both as a solar-thermic collectors and thermal insulators (Figure **15**). Such a system could be designed to function independently of the incidence-angle of the solar radiation, utilizing direct and diffused radiation (mimicking the functionality of the polar bear`s fur).

5. OUTLOOK

The presented spectroscopic and microscopic studies suggest that the light harvesting system in the polar bear fur can only be understood as a synergetic and collective cooperation of many hairs. Light is coupled into the hair fibre via scattering processes, travels for short distance within the hair shaft before being coupled out again by a subsequent scattering process. However, this light is coupled again into a neighbouring hair and so on until the light is either dissipated into heat or absorbed by the bear`s black skin. Therefore, the pelt`s transparent hairs appear white and absorb most of the incident radiation. In addition, the animal`s thermal adaptations include a complementary strategy: trapping the outgoing IR-radiation of body heat between 8000 and 12000 nm; this is supported by the high absorptive capacity of the fur and the absence of significant spectroscopic feature in the entire spectral region.

The polar bear has been confronted with the challenge of looking white, since he inhabits the snow-white arctic environment, in spite of the high transparency of the keratin. The animal`s energy harvesting mechanism is a compromise between its need to maintain a white appearance for camouflage and the advantage of translucent insulation (harnessing solar radiation to heat the subcutaneous and skin surface layers).

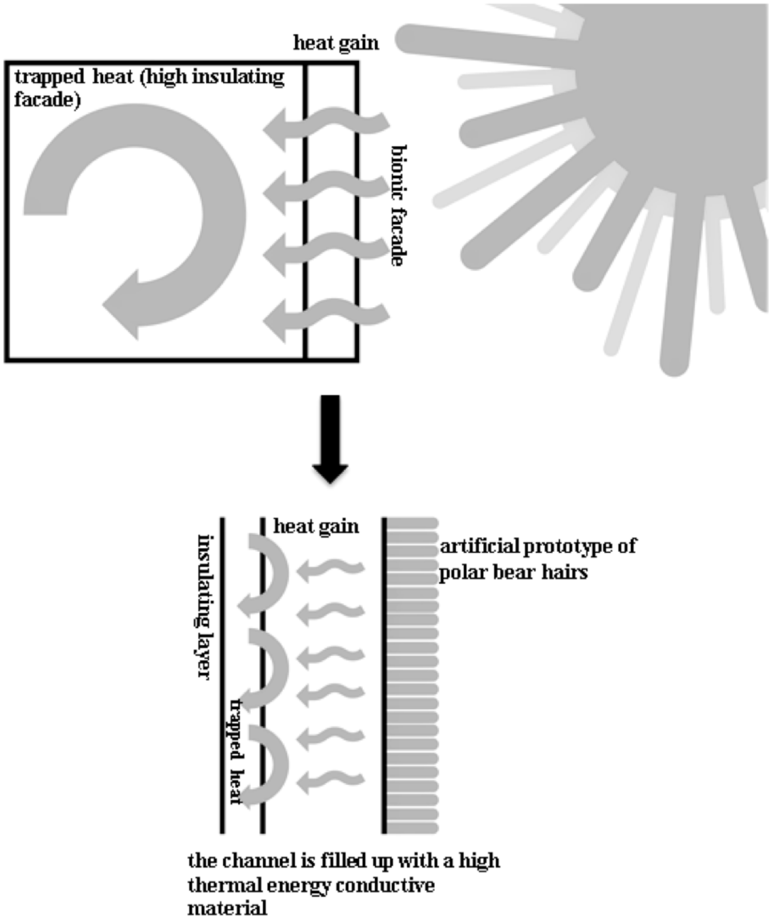


Figure 15: Bionic polar Bear Inspired artificial pelts for facades.

How can ultraviolet light and visible light be a viable source of warmth when it is nearly absent for half a year? The light capturing fur, via the applied non-imaging optics mechanism, is highly adapted to harvest scattered light, which is very abundant in the arctic region. In addition the harvesting of light is only part of the main thermoregulation system, which consists of many behavioural, structural, and morphological adaptations.

Regardless of the total benefit of the polar bears light harvesting technique, the remarkable fact is that it is, for our industry, a hitherto unknown technical idea. The strategy to base a solar energy system on Mie scattering has the advantage that solar light can be harvested in a quite simple way and with only one structured material for the entire solar spectrum. A second advantage is that the same strategy can also cope with thermal energy loss via infrared radiation. A third and very important advantage is, that photochemistry is essentially avoided, since essentially no photochemical energy turnover is happening within the hairs. Membranes based on Mie scattering, if properly designed, promise long-term stability. This should motivate researchers to learn more about this solar energy system and develop technical prototypes.

There are two strategies imaginable to produce biomimetic textiles and artificial pelts for solar active interfaces following the polar bear`s example: One would be to design an industrial strategy to produce artificially plastic fibers, as explained in the section above, preferable of keratin, treated in such a way that they develop scattering centres similar to those in polar bear hairs. The other strategy would be to genetically modify the hair of domestic animals (e.g. sheep) with gene sections from polar bear, to be harvested as wool. The latter strategy should of course involve a careful evaluation of the animals welfare such as the thermal consequences, which, however could be balanced by an appropriate choice of climatic conditions

Last not least, it should be concluded that the polar bear`s optical technology is a fibre-optical one, which however, would not work with individual hairs. The hairs of the transparent pelt have to engage collectively in scattering processes to produce its extraordinary properties.

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