Smart windows passively driven by greenhouse effect

G. Boudan,1,2 E. Eustache,2 P. Garabedian,2 R. Messina,1 and P. Ben-Abdallah1

1Laboratoire Charles Fabry, UMR 8501, Institut d’Optique, CNRS, Université Paris-Saclay, 2 Avenue Augustin Fresnel, 91127 Palaiseau Cedex, France.
2Thales Research and Technology France, 1, Avenue Augustin Fresnel, F-91767 Palaiseau, Cedex France.

(Dated: November 8, 2022)

The rational thermal management of buildings is of major importance for the reduction of the overall primary energy consumption. Smart windows are promising systems which could save a significant part of this energy. Here we introduce a double glazing system made with a thermochromic metal-insulator transition material and a glass layer separated by an air gap which is able to switch from its insulating to its conducting phase thanks to the greenhouse effect occurring in the separation gap. We also show that this passive system can reduce the incoming heat flux by 30% in comparison with a traditional double glazing while maintaining the transmittance around 0.35 over 75% of visible spectrum.

Nowadays buildings consume about 40% of the primary energy used in the world [1]. Therefore their thermal management is a major concern in the context of current global challenge of energy efficiency. Smart windows could play a major role to respond to this challenge. These windows can be used to control heat flux exchanged between the indoor and external environment. One way to achieve this control is by tuning the radiative properties of these systems. Hence, by controlling the overall emissivity/transmittivity of a window surface it is possible to facilitate or reduce heat exchange with the environment and therefore to act directly on the indoor temperature. Several strategies have been proposed so far to perform such a control. For example, single glazings made of thermochromic materials have been suggested [2–4] to tailor the optical properties of windows with respect to their temperature. Among these materials vanadium dioxide (VO2) a metal-insulator transition (MIT) material has been largely investigated. Due to their pronounced change of optical properties in the infrared these phase-change materials have found numerous applications in the fields of thermal management [5–9], energy storage [10] and information treatment [11]. However this material undergoes a reversible structural phase transition at relatively high temperature (TC ~ 68°C) making its employment challenging in smart windows. Moreover, to date, there is no real alternative candidate to this material presenting a pronounced MIT close to the ambient temperature. Electrochromic materials have also been proposed [12, 13] to modify the optical properties of smart windows using an external bias voltage. Hence, by using VO2 solid-electrolyte films, the light transmittance of such gate-controlled smart windows can be dramatically modified by tuning the hydrogen-ion doping through gating voltage. However, although this optical control can operate at ambient temperature it requires an external energy supply. Moreover, electrochromic windows are mainly effective in blocking visible light and not infrared radiation so that their thermal performances remain today very weak.

In the present letter we introduce a passive smart window based on a double glazing system (Fig. 1) realized with a VO2 film deposited on the inner side of one of the two glass panes. The temperature of the VO2 layer is driven by the greenhouse effect occurring between the two panes thanks to the external sunshine in the visible range, by the heat flux radiated in the infrared by the surrounding environment and the inner wall and by the convective exchanges.

Figure 1: Sketch of the passive smart window made with a double glazing of two SiO2 layers separated by a gap filled of noble gas and a VO2 thin film deposited on the inner side of one of the two glass panes. The temperature of the VO2 layer is driven by the greenhouse effect occurring between the two panes thanks to the external sunshine in the visible range, by the heat flux radiated in the infrared by the surrounding environment and the inner wall and by the convective exchanges.
by the external sunshine and the heat flux radiated in the infrared by the external environment and the inner walls we show that our smart-window design results in a significant reduction of the heat flux reaching the inner side, compared to traditional windows, in conjunction with a low reduction of the transmittance in the visible range of the spectrum.

To start let us describe the physical characteristics of the window. Here we assume that the window is in contact with a thermal bath having temperature \( T_1(t) \) and is illuminated by the sun during the day with a time-varying flux \( \Phi_z(t) \) depending on the sun trajectory during the day. For the sake of simplicity, the field radiated by the bath can be assimilated to the field radiated by a blackbody at the same temperature. On its opposite side the window interacts with the thermal bath, and we consider here a double glazing with a cavity filled with a noble gas, such as Argon, and we assume each pane cooled or heated by natural convection on its opposite side. With vertical windows and temperature differences between the panel and its surrounding smaller than \( \Delta T < 50^\circ \text{C} \) the corresponding heat transfer coefficients can be reasonably set to \( h_c = 1 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \) and \( h_{\text{ext, int}} = 5 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \) which correspond to the typical values for vertical panels in these conditions [18–19]. Hence, the power exchanged by convection between each panel and its surrounding is about \( \mathcal{P}_{\text{conv} \rightarrow 3} \sim (h_c + h_{\text{ext, int}}) \Delta T \) that is a third of the solar irradiation. In this preliminary study, we do not include the heat exchanges due to forced convection or turbulent exchanges between each pane and its surrounding environment. These effects as well geometric effects such as the window inclination and sizing will be analyzed in future works. The heat flux across any plane parallel to the interacting surfaces is given by the normal component of Poynting vector

\[
\varphi(z) = (\mathbf{E}(z) \times \mathbf{H}(z)) \cdot \mathbf{e}_z. \tag{3}
\]

Here \( \mathbf{e}_z \) denotes the unit vector normal to the panes of windows, \( \mathbf{E} \) and \( \mathbf{H} \) are the local electric and magnetic fields which are generated by the randomly fluctuating source currents in each solid and by the fields radiated by media 1 and 4 while \( \langle . \rangle \) represents the classical statistical averaging over all field realizations. Using the Fourier decomposition of electric and magnetic fields \( \varphi(z) \) can be recasted in terms of the field correlators \( \mathcal{C}^{\phi\phi}_{j}(\omega, \kappa) = \langle E_{\phi,j}^{+}(\omega, \kappa) E_{\phi,j}^{-\dagger}(\omega, \kappa) \rangle \) of local field amplitudes in polarization \( j \) [20,21]

\[
\varphi(z) = 2\varepsilon_0 c^2 \sum_{j=\pm} \sum_{\phi_1,\phi_2} \int_0^{\infty} \frac{d\omega}{2\pi} \int_{\kappa}^{\kappa + \omega / c} \frac{d\kappa k_z}{2\pi \omega} \mathcal{C}^{\phi\phi}_{j}(\omega, \kappa), \tag{4}
\]

where \( \kappa \) and \( k_z = \sqrt{\omega^2 - \kappa^2} \) denote the parallel and normal components of the wavector. The correlators \( \mathcal{C}^{++}_{j} \) and \( \mathcal{C}^{--}_{j} \) in each region of the system can be written in terms of correlators of fields radiated by each solid and by the component of solar flux, \( \mathcal{P}_{\text{conv} \rightarrow 1} \) the losses/gains due to the convective exchanges and \( C_i \) the heat capacity per unit surface for the pane \( i \) of the window. The power exchanged per unit surface by each plate \( (i = 2, 3) \) with its surrounding by convection is calculated from the convective heat transfer coefficients \( h_c^i \) and \( h_{\text{ext, int}}^i \) (within the cavity formed by the two panes, between the external medium and the external pane and between the inner medium and the internal pane) using the linear Newton’s law of cooling

\[
\mathcal{P}_{\text{conv} \rightarrow 2,3} = h_c(T_{3,2,3} - T_{2,3}) + h_{\text{ext, int}}(T_{1,4} - T_{2,3}), \tag{2}
\]
the external baths. We summarize below the calculation of one of such correlators (say \(C_{i}^{++}\) in the windows cavity), the calculation of all others correlators being similar. The right and left propagating fields \(E_{c}^{\pm}\) in this cavity are related to the fields in the region of baths \(E_{i,4}^{\pm}\) and to the fields \(E_{i}^{\pm}\) (\(i = 2, 3\)) emitted by each pane by the following systems (by omitting to write the polarization for clarity reasons)

\[
E_{c}^{+} = E_{i}^{+} + \rho_{2}^{+} E_{c}^{-} + \tau_{2}^{+} E_{i}^{+}, \quad E_{c}^{-} = E_{i}^{-} + \rho_{3}^{-} E_{c}^{+} + \tau_{3}^{-} E_{i}^{-},
\]

where \(\rho_{i}^{\pm}\) and \(\tau_{i}^{\pm}\) are the reflection and transmission operators of the layer \(i\) toward the right (+) and the left (−), respectively. By solving this system with respect to the cavity field we get

\[
E_{c}^{+} = U_{23}[E_{c}^{+} + \tau_{2}^{+} E_{i}^{+} + \rho_{2}^{+}(E_{c}^{-} + \tau_{3}^{-} E_{i}^{-})], \quad E_{c}^{-} = U_{23}[\rho_{3}^{-} E_{c}^{+} + \tau_{3}^{-} E_{i}^{-} + E_{c}^{-} + \tau_{2}^{+} E_{i}^{+}],
\]

where we have set \(U_{23} = [1 - \rho_{2}^{+} \rho_{3}^{-}]^{-1}\). It follows that the correlators \((++)\) into the cavity reads in term of correlators of fields radiated by each solid

\[
C_{i}^{++} = |U_{23}|^2 [C_{i}^{++}] + |\rho_{2}^{+}|^2 [C_{3}^{--}] + |\tau_{2}^{+}|^2 [C_{i}^{++}],
\]

But, according to the fluctuation dissipation theorem \([22]\), these correlators reads

\[
C_{2}^{++} = S(T_{2})(1 - |\rho_{2}^{+}|^2 - |\tau_{2}^{+}|^2), \quad C_{3}^{--} = S(T_{3})(1 - |\rho_{3}^{-}|^2 - |\tau_{3}^{-}|^2), \quad C_{i}^{++} = S(T_{i}), \quad C_{i}^{--} = S(T_{i}),
\]

with

\[
S(T) = \pi \frac{\omega}{\epsilon_{0}c^{2}} \frac{1}{k_{B}} N(\omega, T),
\]

and \(N(\omega, T) = \frac{k_{B}}{2} \coth(\frac{k_{B}\omega}{2T})\). Finally, the radiative power received by the two panes from the rest of the system (except the sun) reads

\[
\mathcal{P}_2 = \varphi(0) - \varphi(-\delta_{2}), \quad \mathcal{P}_3 = \varphi(d + \delta_{3}) - \varphi(d),
\]

\(\delta_{2}, \delta_{3}\) being the panes thickness.

The solar flux plotted in Fig. 3(b) is calculated from the AM1.5 Global spectrum \([23]\) over a daily cycle for a window facing south. We also assume a sinusoidal variation of the outdoor temperature [Fig. 3-(a)] with a minimal value \(T_{i}^{\min} = 10^\circ C\) at 5 a.m. and a maximal value \(T_{i}^{\max} = 30^\circ C\) at at 4 p.m., corresponding to a typical variation of this temperature during summer. Finally, in order to demonstrate the operating mode of the window we assume the inner wall perfectly absorbing (i.e., \(\epsilon = 1\)).

The time evolution of these two primary sources being very slow in comparison with the thermalization time of the greenhouse effect (\(\sim\) few seconds to the minute), the energy balance Eq. (1) can be solved in the adiabatic approximation.

The solutions \((T_{2}(t), T_{3}(t))\) of this balance equation corresponding to the external conditions (solar flux \(\Phi(t)\), outdoor temperatures \(T_{i}(t)\)) given the indoor temperature \(T_{i} = 25^\circ C\) are plotted in Fig. 4 for different thicknesses of \(\text{VO}_{2}\) film and compared to the thermal state of a simple glass-glass double glazing. As shown in Figs. 4(a) and (b) the temperature of the active layer can reach, at the midday, levels significantly higher than the critical temperature \(T_{C}\). The comparison of \(T_{1}\) (resp. \(T_{2}\)) with the temperatures of a double (glass-glass) glazing of same thickness demonstrates the presence of a strong greenhouse effect in the designed window due to the trapping of the infrared light in the separation gap between the two panes. The magnitude of this effect is directly related to the thickness of \(\text{VO}_{2}\) film. As shown in Figs. 4(a) and (b), the thicker this film the greater is the blocked infrared radiation in the separation gap between the two panes of glazing. The heating induced by this greenhouse effect in the smart window surpasses the one traditionally observed in the traditional double-glazing window by more than 100% with \(\text{VO}_{2}\) film 100 nm thick in \(S_{1}\)-type configuration and it is still 55% higher with a film 10 nm in the same configuration. The physical consequences of this heating are shown in Figs. 4(c) and (d) demonstrating both the thermal and optical performances of this smart window. The net incoming heat flux \(\mathcal{P}_{\text{net}}\), with respect to time, plotted in Fig. 4(c) is drastically reduced in comparison with a traditional window (double glazing \(\text{SiO}_{2}-\text{SiO}_{2}\)). This reduction is approximately 400 W·m⁻² at the midday when the \(\text{VO}_{2}\) film \(d_{\text{VO}_{2}} = 100\) nm thick is deposited on the inner side of the external pane \((S_{1}\) configuration in Fig. 1), a value representing 40% of the solar irradiation at 48.2° latitude and about 55% of the incoming flux through a traditional window. Such isolating behavior exceeds by far the performances of all previous smart windows \([24, 25]\). On the other hand, when the
MIT layer is on the opposite pane (S₂ configuration) the incoming net flux becomes, in comparison, more important, the temperature of this pane being increased by the greenhouse effect. For 10 nm thick VO₂ the thermal insulation is reduced by a third.

Beside the thermal characteristics of the window we show in Fig. 4(d) the transmittance

\[ T(\omega) = \int_0^{\pi/2} [t_s(\omega, \theta) + t_p(\omega, \theta)] \cos \theta \sin \theta d\theta \]  

of the smart window in the visible range for both phases of thermochromic material. Here \( t_s \) (resp. \( t_p \)) denotes the directional spectral transmission of the window under an incident angle \( \theta \) (with respect to the normal, see Fig. 1) in s (resp. p) polarization. Notice that this transmittance depends weakly, in the visible, on the crystallographic state of VO₂ film, the main changes taking place mainly in the infrared. Although relatively small, this transmittance (~35% for 10 nm thick VO₂) over 75% of spectrum is comparable with that of usual double glazing SiO₂-SiO₂. This transmittance falls down to 20% with 100 nm thick VO₂, making the window partially opaque. Nevertheless, this value could be significantly improved using a nanostructured MIT layer without significantly affecting its properties in the infrared, as discussed in Ref. [21]-[27]. However, this could also significantly increase the overall fabrication cost. This problem as well as the optimization of the window will be addressed in a specific study.

In conclusion we have introduced a smart window based on a double glazing made with a SiO₂-VO₂ bilayer which is autonomously thermally and optically regulated by greenhouse effect. This system overcomes the primary weaknesses of thermochromic and electrochromic smart windows. Beyond its application in the development of smart windows for more sustainable buildings, the passive insulation mechanism introduced in the present work could find broader applications in the development of self-regulated insulating materials for complex systems.

Acknowledgments

This research was supported by the French Agence Nationale de la Recherche (ANR), under grant ANR-19-CE08-0034 (PassiveHEAT). P. B.-A. acknowledges discussions with E. Blandre and A. Losquin.

Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

* Electronic address: pba@institutoptique.fr

[1] T. Ramesh, R. Prakash, K. K. Shukla, Energy Build. 42, 1592 (2010).
[2] H. Kim, Y. Kim, K. S. Kim et al., ACS Nano 7, 5769 (2013).
[3] J. Zheng, S. Bao, and P. Jin, Nano Energy 11, 136 (2015).
[4] T. Chang, X. Caoa, L. R. Dedon et al., Nano Energy 44, 256 (2018).
[5] P. Ben-Abdallah and S. A. Biehs, Appl. Phys. Lett., 103, 191907 (2013).
[6] P. Ben-Abdallah, H. Benisty and M. Besbes, J. Appl. Phys. 116, 034306 (2014).
[7] P. Ben-Abdallah and S.-A. Biehs, Phys. Rev. Lett. 112, 044301 (2014).
[8] A. Fiorino, D. Thompson, L. Zhu et al., ACS Nano 12, 5774 (2018).
[9] D. G. Baranov, Y. Xiao, I. A. Nechepurenko et al., Nature Materials 18, 920 (2019).
[10] V. Kubytskyi, S.-A. Biehs and P. Ben-Abdallah, Phys. Rev. Lett. 113, 074301 (2014).
[11] P. Ben-Abdallah and S.-A. Biehs, Phys. Rev. B 94, 241401(R) (2016).
[12] A. Cannavale, U. Ayr, F. Fiorito et al., Energies, 13, 1449 (2020).
[13] S. Chen, Z. Wang, H. Ren et al., Sci. Adv. 5, eaav6815 (2019).
[14] M. M. Qazilbash, M. Brehm, B. G. Chae et al., Science 318, 5857, 1750 (2007).
[15] A. S. Barker, H. W. Verleur, H. J. Guggenheim, Phys. Rev. Lett. 17, 1286 (1966).
[16] H. W. Verleur, A. S. Barker, C. N. Berghund, Phys. Rev. 172, 788 (1968).
[17] Handbook of Optical Constants of Solids, edited by E. Palik (Academic Press, New York, 1998).
[18] H. B. Awbi, Energy and Buildings 28, 219-227 (1998).
[19] W. H. McAdams. Heat Transmission, McGraw-Hill Book Company, (New York, 3rd edition, 1954).
[20] S.-A. Biehs, R. Messina, P.S. Venkataram et al., Rev. Mod. Phys., 93, 025009 (2021).
[21] I. Latella, P. Ben-Abdallah, S.-A. Biehs et al., Phys. Rev. B 95, 205404 (2017).
[22] S.M. Rytov, Y. A. Kravtsov and V. I. Tatarskii, Principles of Statistical Radiophysics, Vol. 3, (Academy of Sciences of USSR, Moscow, 1953).
[23] NREL (2004), Reference Solar Spectral Irradiance: Air Mass 1.5 (rredc.nrel.gov/solar/spectra/am1.5).
[24] M. Feng, X. Bu, J. Yang et al., J. Mater. Sci. 55, 8444 (2020).
[25] Y. Cui, Y. Ke, C. Liu et al., Joule 2, 1707 (2018).
[26] A. Taylor, I. Parkin, N. Noor et al., Opt. Exp. 21, A750 (2013).
[27] S. Liu, C. Y. Tso, H. H. Lee et al., Sci. Rep. 10, 11376 (2020).