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Experimental Implementation and Theoretical Investigation of a Vanadium Dioxide Optical Filter for Bit Error Rate Enhancement of Enhanced Space Shift Keying Visible Light Communication Systems

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Abstract: Visible Light Communication (VLC) systems use light-emitting diode (LED) technology to provide high-capacity optical links. The advantages they offer, such as the high data rate and the low installation and operational cost, have identified them as a significant solution for modern networks. However, such systems are vulnerable to various exogenous factors, with the background sunlight noise having the greatest impact. In order to reduce the negative influence of the background noise effect, optical filters can be used. In this work, for the first time, a low-cost optical vanadium dioxide (VO₂) optical filter has been designed and experimentally implemented based on the requirements of typical and realistic VLC systems in order to significantly increase their performance by reducing the transmittance of background noise. The functionality of the specific filter is investigated by means of its bit error rate (BER) performance estimation, taking into account its experimentally measured characteristics. Numerous results are provided in order to prove the significant performance enhancement of the VLC systems which, as it is shown, reaches almost six orders of magnitude in some cases, using the specific experimental optical filter.

Keywords: bit error rate; VLC; experimental optical filter; eSSK; VO2 filter

1. Introduction

The Visible Light Communication (VLC) systems that use light-emitting diode (LED) technology to transmit the information signal have attracted research and commercial interest during the last few years due to the advantages that they offer [1–8]. The use of the visible electromagnetic (EM) spectrum, between 400 nm and 700 nm, and the high responsivity of LED lamps offer a high data rate performance suitable for modern networks with high capacity requirements [9]. Additionally, the visible EM spectrum is environmentally and biologically safe and no license is required to use it, while, due to the evolution of semiconductor technology, low-cost and low energy consumption LED lamps are used. All these advantages have identified VLC systems as a highly accessible solution for next-generation communication networks [10,11], as well as for smart home and smart city applications [12,13]. However, such systems can be affected by various factors that degrade their performance and most of them are difficult to predict or eliminate.

The main factor that significantly affects and decreases the performance of VLC systems is the background noise, which mainly originates from sunlight radiation, and this is the main reason why such communication systems are mostly used for indoor applications [14]. One of the most



for data transmission, reducing the background noise. The proposed optical filter consists of a thin densified film of VO₂ deposited on a glass substrate. Its filtering capability utilizes the wavelength dependence of the optical transmittance of metallic phase VO₂. In comparison to other (thin film) optical filters, such as interference (dichroic) filters [16], or other proposed filtering devices [17], it can be argued that VO₂ can be as efficient but, in addition, being a single layer, it is easily fabricated by applying established experimental techniques, making it a more economical choice. Furthermore, the luminous transmittance of pure undoped VO₂ might be favorably employed to a greater degree in the proposed filter as compared to, for example, the application of VO₂ films as shielding layers in smart windows [18]. For this latter application, the presently achieved luminous transmittance of undoped VO₂ thin films scarcely meets the requirements and a great research effort is devoted to the corresponding improvement on an international level. It should, however, be mentioned here that the transmittance performance of the proposed optical filter can further be improved, as will be discussed in Section 2 of the present work.

To investigate the performance of the proposed filter, four Red Green Blue (RGB) LED lamps are used in order to deploy a VLC communication system in an indoor environment in the presence of sunlight radiation. The room dimensions employed in the numerical calculations are not exactly the "typical ones", but a larger space has been chosen, in order to extract clearer conclusions about the effectiveness of the experimental optical filter under consideration, for the VLC links. The modulation scheme of space shift keying (SSK) which is used has proved to be a very effective technique for increasing the VLC system performance [19,20]. According to this technique, each LED lamp is active in a specific timeslot, transmitting a different symbol. In conventional SSK, every transmitter has an equal pulse duration and amplitude, but in order to further enhance this modulation technique, the pulse for each symbol has a unique time duration, creating the enhanced space shift keying (eSSK) modulation technique [21,22]. In order to investigate how the adjustment of an optical filter at the receiver enhances its performance, the bit error rate (BER) metric will be estimated for an indoor environment in the presence of sunlight radiation. To the best of our knowledge, it is the first time that such a low-cost, thin-film, VO₂ optical filter has been proposed and experimentally evaluated as a component of a typical VLC system in order to reduce the background noise and improve the performance characteristics of the link. More specifically, as it will be shown in Section 6, taking into account the experimentally determined properties of the optical filter, the BER performance of a typical VLC link reaches a six orders of magnitude improvement.

The remainder of the work is organized as follows: In Section 2, the VO_2 optical filter design and implementation will be analyzed; in Section 3, the characteristics of the system model will be presented; in Section 4, the signal-to-noise ratio (SNR) of the system will be estimated; in Section 5, the BER performance will be estimated; and in Section 6, the corresponding numerical results will be presented.

2. Vanadium Dioxide Filter Elaboration Procedure

Bulk vanadium dioxide undergoes a fully reversible semiconductor to metal transition (SMT) when heated above T_{SMT} = 340 K, which is accompanied by a structural transition. The dramatic changes of the electrical, optical, and thermal properties associated with the SMT transition have also been experimentally verified in thin VO₂ films with thicknesses down to tens of nm [23,24]. Above T_{SMT} , VO₂ thin films are quite transparent at around 650nm, while they exhibit enhanced reflectance/absorption both in the UV and near-IR region. For wavelengths around 650 nm, the absolute transparency of VO₂ films can be enhanced by tailoring the chemical composition and microstructure

of the material, as well as its geometrical features (thickness). This spectral variation of optical transparency appears very beneficial for an optical communication system employing a VO₂ thin film as an optical filter in front of the receiver in order to reduce the background noise. The implementation of a VO₂ optical filter might require the integration of a resistor in the form of a metal film as a heater in order to retain the film in its metallic phase and thus take advantage of its full filtering capability. Alternatively, the transition temperature T_{SMT} might be tuned to the operation temperature of the

Within the present investigation, high-quality VO₂ films have been obtained by physical vapor deposition (PVD), which was employed to deposit V₂O₅ films on transparent, i.e., glass, substrates and conduct subsequent thermal reduction. Specifically, the V₂O₅ films, with an estimated thickness of 240 nm, were reduced to monoclinic VO₂ (M1) by annealing under steady nitrogen (N₂) gas flow with a pressure of 0.4 mbar, at an annealing temperature of about 500 °C for 3 h. The transformation of V₂O₅ to pure monoclinic VO₂ (M1) phase was monitored by x-ray diffraction (XRD) analysis on a Siemens D 5000 diffractometer with Cu K α radiation at a 20-step of 0.03° and a counting time of 2 s/step.

device by the appropriate doping of VO₂, as extensively researched in the literature [25–33].

To investigate the changes of the electrical and optical properties of VO₂ films around the SMT, electrical resistance was measured in the temperature range of 300–380 K where the SMT takes place, using a 225 Keithley current source and a DMM 2000 Keithley voltmeter. For the same purpose, optical transmittance was measured on the same specimen, at a wavelength of $\lambda = 1550$ nm within the SMT temperature region, i.e., 300–350 K. We used an LED diode emitting at 1550 nm as a source, while the detection was performed by an InGaAs photodiode. In addition, optical transmittance was measured within the spectral region 400–1000 nm at room temperature and $T > T_{SMT}$. A Xe lamp monochromated through an Oriel monochromator was used as a light source for the transmittance and a calibrated silicon photodiode was used for the detection of the transmitted light. In our calculations, we took into account the contribution of the bare substrate. For the transmittance experiments, we designed a special heating stage to achieve isothermal conditions over the film area and their temperature was monitored by a NiCr–Constantan thermocouple in contact with the films.

According to the results shown in Figure 1a, the low-current DC-electrical resistance of a VO₂ thin film on a glass substrate exhibits a sharp SMT at T_{SMT} = 340K, resulting in a drop of approximately three orders of magnitude. The same film exhibited an abrupt decrease of 40% of the optical transmittance in the near infrared region, i.e., λ = 1550 nm, at T_{SMT} , as shown in Figure 1b. The narrow (~5K) thermal hysteresis loops depicted in Figure 1 for both measurements can be attributed to the first-order structural (monoclinic to tetragonal (rutile)) transition accompanying the SMT transition.



Figure 1. (a) Temperature dependence of the electrical resistance of a VO₂ thin film on glass at T = 300–380 K, as has been experimentally measured; (b) temperature dependence of the optical transmittance of a VO₂ thin film on glass at λ = 1550 nm for T = 300–350 K, as has been experimentally measured.

The results of a typical measurement of the optical transmittance within the spectral range 400 nm $\leq \lambda \leq 1000$ nm at T ≈ 300 K and at T = 370 K are shown in Figure 2. As presented in Figure 2, the rutile (metallic) VO₂ film (T = 370 K) exhibits remarkably low transmittance between 350 nm $\leq \lambda \leq 500$ nm, combined with a progressive decrease of the transmittance in the near infrared region upon an increasing wavelength. In the monoclinic insulating phase, i.e., at T = 300 K $< T_{SMT}$, the transmittance increases steadily for any wavelength, while it is almost identical to that of the rutile phase in the UV region, see Figure 2. Accordingly, the overall spectral variation of the transmittance attains a "hanging bell" shape in the visible light region, with a broad peak centered at 650 nm—where an overall transmittance of 25% is obtained—suggesting a unique radiation-shielding ability of VO₂ thin films extending on both sides of the visible light region. Therefore, rutile VO₂ films appear highly promising as absorption/reflectance materials for solar radiation shielding performance.



Figure 2. Optical transmittance of a VO₂ thin film on glass below (300 K) and above (370 K) T_{SMT} upon wavelength variation in the range 400–1000 nm.

The experimental results shown in Figures 1 and 2 are in good agreement with recent experimental [34-38], as well as theoretical, literature reports [39]. The sharp decrease of both the electrical resistance and T-dependent IR-transmittance observed around the SMT transition indicates the high-phase purity and adequate crystallinity of the VO_2 films, in accordance with the obtained XRD patterns. The spectral variation of the transmittance of rutile VO₂ shown in Figure 2 at $\lambda \ge 750$ nm reflects a synergetic combination of simultaneously increasing reflectivity and absorption [40] and is thus governed by the intrinsic properties of the material. The strong absorption in the IR region is likely due [41] to the plasma oscillation of the conduction electrons in the metallic phase, indicating a direct correlation with the electrical conductivity of the material in the metallic phase. This, in turn, can be reasonably closely related to the tunability of the filter, as an increase of the electrical conductivity of metallic VO_2 can be expected to result in a higher rejection (i.e., lower transmittance) of near IR radiation. On the other hand, it should be remarked that the steep increase of the optical transmittance at 450 nm $\leq \lambda \leq 600$ nm shown in Figure 2 is insensitive to the electrical conduction, as well as changes of the crystal symmetry and the structural transition (monoclinic to rutile) of the material. This effect should thus be related to fundamental band-structural features of VO_2 , like the band gap between valence bands formed by O 2p states and the π^* band, in accordance with previous work [28]. Within this scenario, narrowing the band pass width of the proposed filter might be attempted by band gap engineering of the material. A decrease of the band gap width would be desirable for this specific application, which could involve the doping of VO₂ with properly selected cations. However, it should be emphasized that no such effort has been reported yet, to the best of our knowledge.

According to recent experimental data, the spectral variation of the transmittance of a 50 nm and 100 nm rutile VO₂ film coating-dispersed nanoparticles, as well as of a 50 nm VO₂ compacted film, forms a "hanging bell" shape in the visible light region [40,42]. The largest transmittance values are found at 670 nm, with an overall transmittance of 53%, 29.5%, and 36.2% respectively, showing that the maximum transmittance increases as the thickness of the films decreases. Alternatively, the luminous transmittance of rutile VO₂ films might also be enhanced by adequate doping. For example, Fe-doped VO₂ thin films prepared on glass substrates by direct current (DC) magnetron sputtering with a thickness of about 150 nm, show an increase of optical transmittance at 670 nm with the increase of Fe-content, maintaining an almost symmetric "hanging bell" shape at around this wavelength [33].

3. System Model

We assume that four white RGB LED lamps are installed on the ceiling of a typical rectangular room for illumination and data transmission using the red color, i.e., a wavelength range between 600 nm and 700 nm. A simple pattern for the placement of LED lamps that is mostly used in indoor environments will be used and is presented in Figure 3.



Figure 3. Ceiling overview of the light-emitting diode (LED) pattern.

The emission pattern of each LED lamp of Figure 3 follows the Lambertian model, which accurately describes the spatial power diffusion of an LED lamp [43–46]. Therefore, assuming that the optical power transmitted is P_t , the power at the receiver, P_r , will be given as [43,44]

$$P_r = P_t A \frac{m+1}{2\pi d^2} \cos^m(\varphi) \mathcal{T}_s(\psi) \cos(\psi) , \ 0 \le \psi \le \Psi_c$$
(1)

where $m = -\ln(2)/\ln(\cos(\varphi))$ is the order of emission, φ is the semi-angle at half power, A is the physical area of the receiver's photodiode, d is the distance between the transmitter and the receiver, ψ is the angle of normalized irradiance, $T_s(\psi)$ is the gain of the optical filter, and Ψ_c stands for the width of the field of view (FOV) at the receiver.

4. SNR Estimation

The signal-to-noise ratio (SNR) represents a very significant parameter for the communication systems. This parameter is the ratio of the signal's power to the power of the noise and can be calculated as [40,44]

$$SNR = \frac{P_r}{\sigma_{tot}^2}$$
(2)

where σ_{tot}^2 is the total noise variance and is given as [40,44]

$$\sigma_{tot}^2 = \sigma_{thermal}^2 + \sigma_{shot}^2 \tag{3}$$

with $\sigma_{thermal}$ being the variance of thermal noise that is generated by the thermal agitation of charge carriers inside a conductor and σ_{shot} is the shot noise due to ambient light. These variances can be estimated through the following mathematical expressions [43,47]:

$$\sigma_{thermal}^{2} = \frac{8\pi k T_{k} n A I_{2} B^{2}}{G} + \frac{16\pi^{2} k T_{k} \Gamma n^{2} A^{2} I_{3} B^{3}}{g_{m}}$$
(4)

and

$$\sigma_{shot}^2 = 2q\gamma P_r B + 2q\gamma P_{bg} I_2 B \tag{5}$$

where *k* stands for the Boltzmann's constant, *G* is the open loop voltage gain, *A* is the physical area of the receiver, T_k is the absolute temperature, I_2 and I_3 are noise bandwidth factors, *n* is the capacitance of the photo detector per unit area, g_m is the transconductance, *B* is the noise bandwidth, *q* is the electronic charge, and P_{bg} is the background noise power.

Assuming that the background noise of the system depends on sunlight radiation, P_{bg} , can be estimated as [14]

$$P_{bg} = E_{\rm det} T_0 A n_{ri}^2 \tag{6}$$

where T_0 is the peak filter transmission coefficient, n_{ri} is the refractive index of the lens, and E_{det} is the irradiance within the spectral range of the receiver. Additionally, E_{det} is the irradiance of the receiver between the wavelengths λ_1 , λ_2 and can be estimated as [14]

$$E_{\text{det}} = \int_{\lambda_1}^{\lambda_2} \frac{S_{peak}W(\lambda)}{\max[W(\lambda)]} d\lambda$$
(7)

where S_{peak} is the peak irradiance and $W(\lambda)$ is the spectral irradiance of a black body radiation model and is given as [14]

$$W(\lambda) = \frac{1}{\lambda^5} \left(\frac{2\pi h_p c^2}{e^{\frac{h_p c}{\lambda K T_B}} - 1} \right)$$
(8)

where h_p is the Planck's constant, c is the speed of light in a vacuum, and T_B is the average surface temperature of the Sun in Kelvin degrees. The integral of Equation (7) cannot be solved analytically, so the accurate numerical method of Monte Carlo is used in order to estimate the solar background irradiance at the receiver, using 10⁶ random samples. In order to improve the SNR of the system, the VO₂ filter implemented can be installed at the receiver in order to reduce the sunlight radiation received. According to Figure 2, the filter is able to reduce the transmittance of the sunlight background noise power, especially for wavelengths lower that 600 nm. Furthermore, the transmittance presents its peak value at 650 nm, representing the wavelength at which the information is transmitted, so power reduction of the signal will be less than the reduction of the noise. This characteristic is very important for the selection of a suitable optical filter.

5. BER Estimation for eSSK

In order to examine how the use of the optical filter affects the performance of the VLC system, its BER performance is investigated. The modulation technique of SSK will be implemented in this VLC system. This technique is a kind of spatial modulation where every LED lamp will transmit a different symbol when it is on. For N_b bit per symbol, the number of symbols N_s that can be created is [48]

$$N_s = 2^{N_b} \tag{9}$$

Therefore, for 2 bit per symbol, four transmitters are required, one for each symbol. In order to reduce the probability of error, different pulse durations for each symbol can be used by deploying the

technique of eSSK. More specifically, the time duration of each symbol will be $\tau_i T$, with T being the duration of symbol of the SSK technique and τ_i being the factor that corresponds to the specific pulse width in eSSK.

The BER for the eSSK scheme is given as [21,22]

$$BER \le \frac{4}{N(N-1)\log_2(M)} \sum_{j=1}^{N-1} \sum_{i=j+1}^{N} Q\left(\sqrt{\frac{TN}{4S}SNR\left(\|\tau_i h_{i1} - \tau_j h_{j1}\|_F\right)^2}\right)$$
(10)

with *N* being the number of transmitters; *M* representing the number of symbols of the system; $S = \sum_{i=1}^{N} \tau_i$, $\|.\|_F$ standing for the Frobenius norm for matrices; and h_{ik} being the channel gain between the *i*-th transmitter and the *k*-th receiver, where, for our system, k = 1, consisting of the channel's gain matrix $H(t) = \begin{bmatrix} h_{11} & h_{12} & h_{13} & \dots & h_{1N} \end{bmatrix}^T$ [21,22]. The channel gain matrix, H(t), for every transmitter can be calculated as the ratio of the total received optical power on the receiver to the transmitted optical power [49]:

$$h_{i1} = \frac{P_{r_i}}{P_{t_i}} \tag{11}$$

6. Numerical Results

In this section, the numerical outcomes for the BER of an eSSK VLC system are presented. The LED transmitters are installed on the ceiling of a typical room with the dimensions $10 \text{ m} \times 6 \text{ m} \times 3 \text{ m}$ in the following coordinates: LED1(2,3), LED2(4,3), LED3(6,3), and LED4(8,3). The length and width of the room were chosen to be greater than the standard model, i.e., $5 \text{ m} \times 5 \text{ m} \times 5 \text{ m}$, in order to cover more space and have an extensive view of the results. However, using the above mentioned expressions, the system's performance can be accurately estimated for any choice of room dimensions. The receiver is placed at the plane of 1.5 m above the floor. The technical characteristics of the LED transmitters and the receiver, which constitute typical values for realistic VLC systems, are presented in Table 1.

Parameter Value Transmitted Optical Power—Pt 20 W 35° Semi-angle at half power— Φ_s 70° Receivers FOV 1 cm^2 Physical Area of the receiver-A 1.5 Refractive index of the lens-n_{ri} 297 K Absolute temperature of the room $-T_k$ $1.12\;\mu m^{-2}$ Photodetector's capacitance-n Noise bandwidth factor I₂ 0.562 0.0868 Noise bandwidth factor I₃ Noise Bandwidth—B 175 MHz Open loop voltage Gain-G 10 1.5 Channel noise factor—Γ 30 ms Transconductance-gm

 Table 1. Values of noise and system parameters.

In Figure 4, the BER performance of the specific VLC system, without the use of the VO₂ optical filter, is presented. The maximum and minimum values of the BER are 0.38 and 8.1×10^{-9} , respectively.

It is clear that the performance of the VLC system degrades at the edges of the room, where the received power is lower and as a result, the SNR of the system decreases significantly compared with the values which are obtained in the center. Additionally, it can also be observed that the BER increases in the areas between the LED lamps, where the values of channel gain are almost the same for two LED transmitters and thus, the receiver cannot easily recognize the source of the signal.



Figure 4. Bit error rate (BER) of the visible light communication (VLC) system under consideration, without the VO₂ optical filter.

In Figure 5, the BER results are presented in the case where the VO₂ optical filter is used at the receiver of the VLC system. It can be easily seen that the use of the filter can greatly increase the performance of the VLC system as the BER values lie between a minimum value of 1.5×10^{-15} and a maximum of 0.33. Therefore, the BER performance improvement which has been achieved is significant as it is almost six orders of magnitude better, in the best case.



Figure 5. Bit error rate (BER) of the visible light communication (VLC) system under consideration, using the VO₂ optical filter at the receiver.

Figure 6 shows the BER performance of the VLC system when no filter is applied. Figure 7 shows the effect of using the VO₂ filter. More specifically, in the colored area on the left of the panels, in both

figures, the BER performance of the system is lower than 1×10^{-6} , which is an average value of BER for the specific VLC system. It can be seen that the application of the optical filter significantly increases the area with a lower BER, making the VLC system much more reliable.



Figure 6. Areas with a bit error rate (BER) $\leq 1 \times 10^{-6}$ for the case where no filter is applied in the visible light communication (VLC) system.



Figure 7. Areas with a bit error rate (BER) $\leq 1 \times 10^{-6}$ for case where the VO₂ filter is applied at the receiver of the visible light communication (VLC) system.

Summarizing the above results, it is demonstrated that the BER performance of the specific VLC system using VO₂ as an optical filter in front of the receiver has been remarkably improved. Specifically, according to the numerical results, the maximum and minimum values of the BER are decreased from 0.38 to 0.33 and 8.1×10^{-9} to 1.5×10^{-15} , respectively. In addition, Figures 6 and 7 show that the effect of using the proposed filter increases the area with a lower BER. Therefore, it is clearly evidenced that the use of a VO₂ thin film as an optical filter in VLC links results in a significant enhancement of their performance. Even higher improvement could be achieved if the transmittance bandwidth of VO₂ thin films was narrowed by displacing the shorter cut-off wavelength to values closer to 600 nm in order to favorably exclude sunlight noise peaking at 500 nm. This might be accomplished with adequate doping, resulting in bandgap narrowing of VO₂ thin films. Apart from this potentiality, the decrease of the thickness of the film, as has been already mentioned, provides a straightforward possibility to boost the optical transmittance at 600–700 nm. Therefore, our present results and the mentioned optimization possibilities provide convincing evidence for the use of VO₂ thin films as a greatly efficient optical filter in VLC links.

7. Conclusions

In this work, the experimental design and implementation of a vanadium dioxide thin film as an optical band-pass filter, in order to be used in a typical VLC link, is presented. Exploiting its properties, the performance of a realistic VLC system using the specific optical filter for reducing the sunlight

background noise is investigated. The optical system is assumed to use the eSSK technique and its BER performance is estimated. From the presented results, it is demonstrated that the use of the optical filter can significantly alter the capabilities of the system, by increasing the BER performance by up to six orders of magnitude in many cases and thus appears suitable for high-performance networks. Moreover, the radiation shielding performance of VO₂ optical filters can be further improved, either by increasing the transmittance for the wavelength employed as the signal carrier or/and by making the transmittance curve much narrower. A further investigation is currently under way to improve the performance of the VO₂ filter by reducing the film thickness and using dopants in order to engineer the energy band gap of VO₂ and thus its transmittance spectrum.

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