Semi-transparent solar cells indifferent to ambient lighting for LiFi Application

Emilie Bialic
Advanced R&D Division, SunPartner Technologies
240 ave. Olivier Perroy, 13106 Rousset cedex - France
Email: Bialic.Emilie@gmail.com

***Abstract*—Light-Fidelity (LiFi) is the communication technology, which utilizes LEDs for both illumination and data transmission with a bidirectional link. In order to enhance the users mobility for indoor or outdoor environment, it is essential to choose the most appropriate receiver. LiFi systems suffer of a lack of receiver solutions about two great LiFi problematics: the integration of the receiver into mobile devices such as smartphones and the receiver capacity to work in indoor and outdoor configurations without complexifying to the system. SunPartner Technologies develops specific semi-transparent solar cells to solve these two problematics. In this paper, we show the main results concerning the ambient lighting effects obtained by semi-transparent photovoltaic modules developed by SunPartner Technologies. In particular, we show through LiFi measurements, that we can obtain three different SNR responses to ambient lighting increase. The conventional effect is obtained when the SNR decreases with the ambient lighting increase. The unusual effect concerns the SNR increase when the ambient lighting increases. Finally, the saturation stability effects show a constant SNR level for different ambient lighting. Through this research, we designed a specific semi-transparent photovoltaic module optimized for LiFi application and we performed a demonstrator that allows streaming-video using this specific photovoltaic module.**

I. Introduction

Recently, research on Light-Fidelity (LiFi) has gained huge interest. LiFi refers to Visible Light Communication (VLC) technology that delivers a high-speed bidirectional link [1],[2]. This kind of technology works in similar manner as WiFi. In such a communication system, an optical sensor translates the received modulation flux sent by a LED source into an electrical signal which is decoded. Nevertheless, there are still two great LiFi challenges: the integration of the receiver in mobile devices such as smartphones and the receiver capacity to work in indoor and outdoor configurations without adding complexity to the system. A semi-transparent photovoltaic (PV) module integrated into the screen of a mobile device may be a good candidate for a relevant solution for both indoor and outdoor applications. In this paper, we present such a solution developed by SunPartner Technologies called Wysips® Crystal. We have shown that Wysips® Crystal modules generate same ambient lighting effects as commercial photovoltaic modules when these Wysips® modules are only optimized for energy harvesting. In next section, we prove that we can overpass this kind of problematic in designing specific LiFi modules called Wysips® Crystal Connect.

978-1-5090-2609-8/16/$31.00 © 2016 IEEE

June 1, 2016

II. LiFi experimental test bed

In order to assess the specific characteristics of semi-transparent photovoltaic LiFi receivers, we decided to characterize in details the SNR response. For this, we choose to use an experimental setup which connects software-based DCO (Direct Current Optical)-OFDM emitter and receiver to hardware optical front-ends. This setup has been developed by a research public organism, called CEA (Commissariat l'Energie Atomique et aux Energies Alternatives) [4].

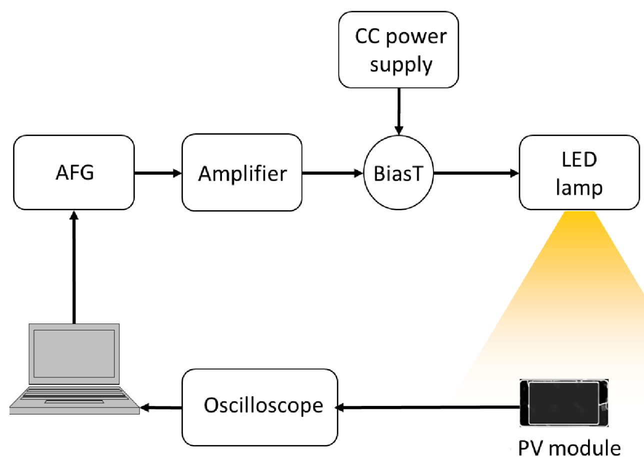


Fig. 1. CEA Leti experimental LiFi Test-bed

A. OFDM signal

The LED source is polarized (DC voltage) before adding an analog bipolar OFDM signal. OFDM signal is generated by the software based DCO-OFDM emitter with 64-FFT and carries 31 subcarriers from DC to 1.2 MHz, 2.4 MHz or 5.5 MHz function of the module capabilities. Each subcarrier is QPSK-modulated and each frame consists in 100 OFDM symbols of 64 samples preceded by 8-sample cyclic prefix. Such a cyclic prefix length is large enough to avoid inter symbol interferences when considering our optical propagation channel.

A clipping level at 80% of maximum value is chosen, in order to achieve a trade-off between the LED linearity range and the clipping noise. The signal is then re-sampled at higher frequency and then passed through an anti-aliasing filter. This discrete OFDM signal is sent to an Arbitrary Function Generator (Tektronix AFG 3102) which converts it into an analog signal with a 14-bit DAC resolution. Then, this OFDM signal goes through an amplifier (MiniCircuit ZHL-32A) to reach a modulation depth between 30% and 50% of the current.

A Bias-Tee (Picosecond 5575A) adds this analog OFDM signal to constant current coming from a power supply. The resulting AC+DC unipolar signal is injected into the LED. We choose the downlight Nova Polaris from Novaday (ND-MR-003-830-30-DR).

B. LiFi reception

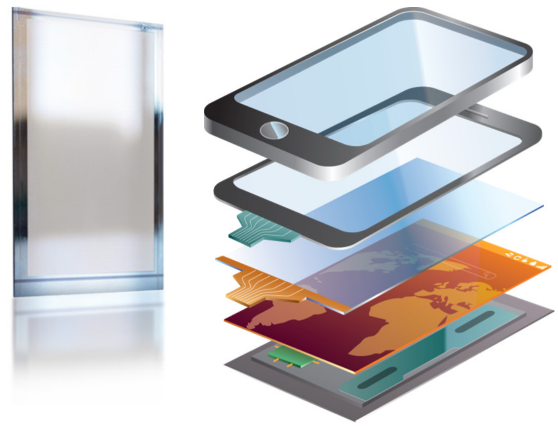
At the receiver's side, different kinds of semi-transparent PV modules are tested to evaluate their performances. Their DC component is removed by the software-based DCO-OFDM digital processing at reception. Receiver modules are in front of the LED lamp and aligned to it. This ensures a direct line-of-sight between the LED source and the photodetector. The output of the photodetector is then sampled by a digital oscilloscope (Tektronix DPO TDS7054) triggered by the AFG to simulate perfect synchronization. Obtained signal is then sent back to the Matlab DCO-OFDM post-processing chain to perform the data reception. For each frame, channel estimation is performed and a zero- forcing equalization is done. Then, the SNR on each sub-carrier is estimated.

It can be noticed that tested photovoltaic modules are directly connected to the oscilloscope with no need of analog circuitry such as trans-impedance amplifiers which are always used with photodiode (PD) or avalanche photodiode (APD). It reveals that these solar cells are able to provide enough signal power to deliver sufficient voltage amplitude under a 50-Ohms termination such as the one of the oscilloscope even if the module are about $1cm^2$.

III. Semi-transparent solar cells

In order to increase mobile device battery lifetime, photovoltaic component is one of the way to provide energy, especially for outdoor application. For aesthetic application with displays, the main difficulty is to find a location on the device for the photovoltaic module without degrading the aesthetics. That is why, SunPartner Technologies developed specific semi-transparent photovoltaic component integrated into screens to ensure a good image quality as it is presented on Fig. 2. The structure is based on thin film silicon solar cell with invisible areas and special contacting scheme. This contacting design allows a metallic grid to collect positive carrier (holes) where they are generated limiting the transport into the TCO. This metallic grid connected to the front contact is as well invisible to the naked eye since it is placed behind the PV areas on a second level insulated with the back contact electrode by a dielectric layer [3].

Nevertheless, these kind of photovoltaic modules could be used as LiFi receivers and optimized for these applications. In the first experiment, we choose to compare the performances



(a) Wysips®Crystal (b) Integration into a phone

Fig. 2. Wysips®Crystal module and integration

of two modules. They have both $1cm^2$ area, same design to generate semi-transparency (33% of photovoltaic surface), same stack. Nevertheless, the first one does not have a metallic grid (W.G. (cyan curves) Fig. 3) but the second one has a metallic grid (G. (purple curves) Fig. 3) to collect positive carriers. We choose to use a LiFi signal about 6600 Lux LiFi and an ambient lighting about 9600 Lux DC coming from an external source. The Fig. 3 show that both the modules present the same kind of behaviors when ambient lighting is adding but the channel attenuation is worse when the module does not have a metallic grid. The particularity of the metallic grid is to enhance the signal level (purple curves) and consequently to improve the channel attenuation as it is shown in Fig. 3.

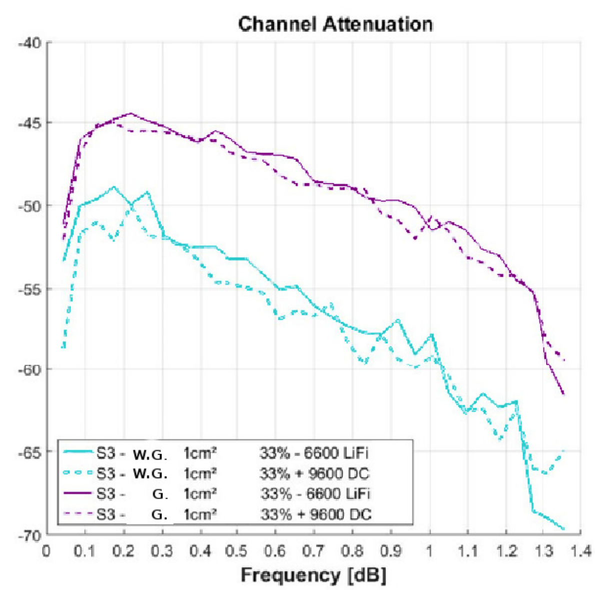


Fig. 3. Semi-transparent modules without (W.G.) and with metallic grid (G.)

SunPartner Technologies choose to develop specific semi-transparent solar cells for LiFi application. In a first step, our main goal was to increase the bandwidth of our module to develop a high data rate system based on this kind of technology. In the second step, we optimized our Wysips®Crystal Connect with the aim of reducing as much as possible the ambient lighting saturation effects.

IV. Ambient Lighting Effects

In this section, we compare ambient lighting effects obtained for different designs of semi-transparent PV modules. In all experiments, the experience consists in adding a huge ambient light (in Lux DC) coming from an external source (Nova Atria Direct R170: reference ND-DL-101-840) to observe the saturation due to high ambient lighting levels.

A. Conventional ambient lighting effects

In order to show that our semi-transparent PV modules can have conventional ambient lighting effects as standard opaque thin film solar cells, we compared the published CIGS results [4] and those non-optimized G. (with grid) semi-transparent modules to perform in energy harvesting.

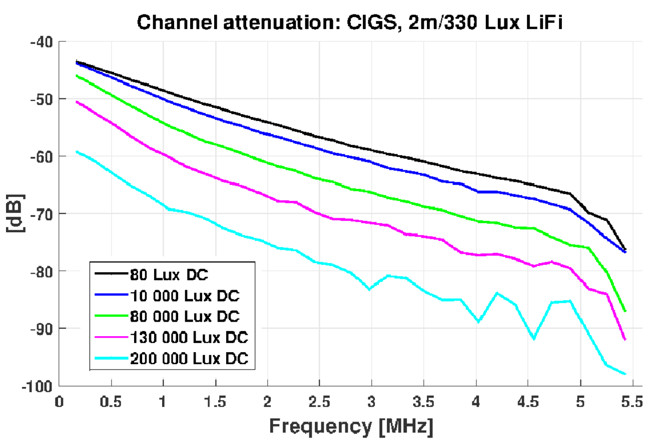


Fig. 4. CIGS signal LiFi & DC responses

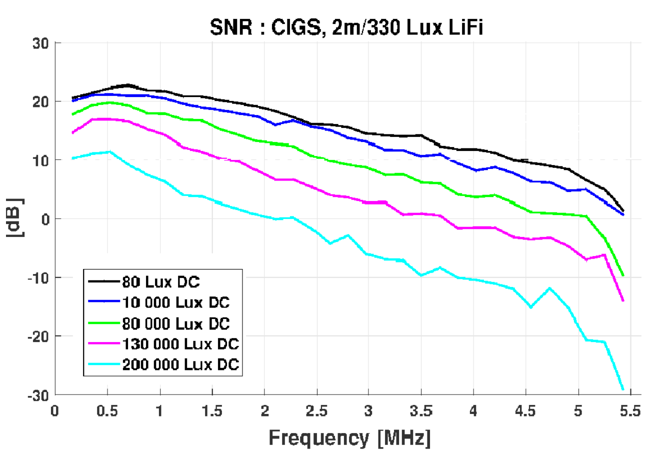


Fig. 5. CIGS SNR LiFi & DC responses

For the CIGS experiment, useful light signal coming from DCO-OFDM LED lamp is maintained around 330 Lux. The distance between the LED lamp and the CIGS module is about 2m. The curves in Fig. 4 and 5 show a classical ambient lighting saturation effect for both the channel attenuation and the SNR. For fixed LiFi signal, when the ambient lighting level increases, both the channel attenuation and the SNR decrease.

For the Wysips®Crystal experiment, the light signal coming from DCO-OFDM LED lamp is maintained around 6600 Lux.

If the G. semi-transparent modules were only optimized for energy harvesting and not specifically for LiFi applications, we obtained the same kind of saturation effects as it is shown in Fig. 6 and 7. When ambient lighting is added, the channel attenuation and the SNR decrease.

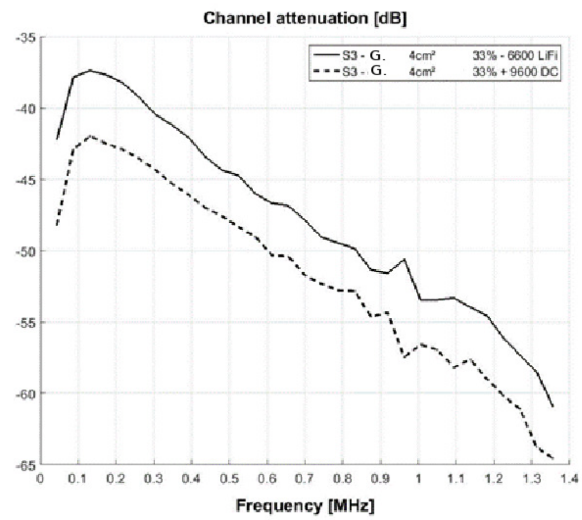


Fig. 6. Wysips®Crystal signal LiFi & DC responses

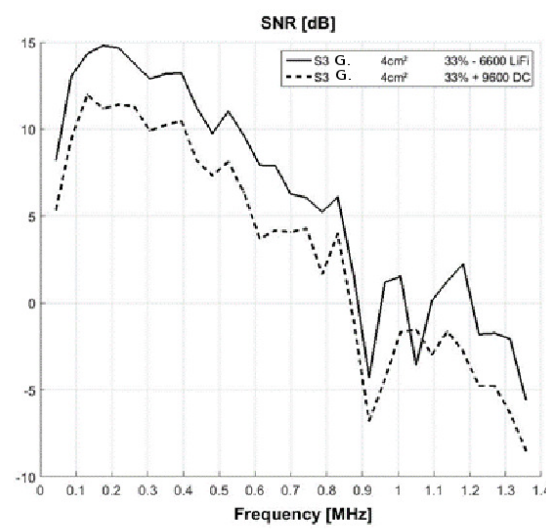


Fig. 7. Wysips®Crystal LiFi & DC responses

B. Unusual ambient lighting effects

As published in [4], we designed photovoltaic modules in order to improve their LiFi performances when ambient lighting is added. The main results are remained in Fig. 8 and 9. This experiment considers two different LiFi signal levels (9 000 and 72 000 Lux LiFi) and two ambient lighting levels (41 000 and 180 000 Lux DC). At constant LiFi signal level, when the ambient lighting increases, the channel attenuation becomes worse (Fig. 8) but the SNR increases (Fig. 9).

Nevertheless, to simplify the complexity of the LiFi modem in reducing the treatment times by using a simple algorithm, it is better if the characteristics of the SNR are the same in all type of configurations. After few months of research, we obtained the first modules that present these kind of characteristics. The principle results are presented in the following section.

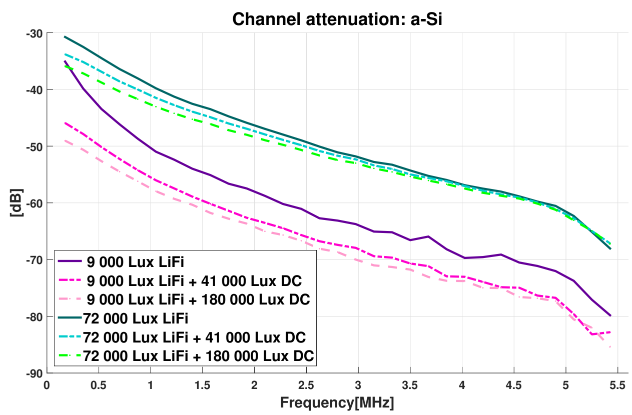


Fig. 8. a-Si LiFi signal & DC responses

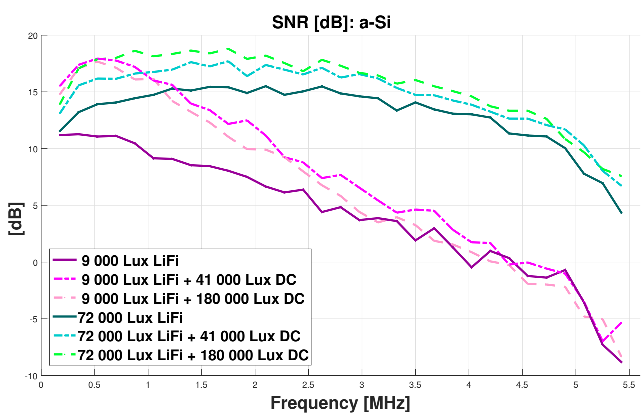


Fig. 9. a-Si LiFi SNR & DC responses

C. Saturation stability ambient lighting effects

We show in this section the first results of our semi-transparent photovoltaic modules designed to present the same SNR in LiFi only configurations and in ambient lighting configurations. The results are presented in Fig. 10 and 11. In this experiment, our DC source generated ambient lighting from 0 to 80 000 Lux and we compare the effects of ambient lightings at two different signal levels : 6 600 Lux LiFi (cyan curves) and 36 000 Lux LiFi (deep blue curves). When we work at a constant LiFi signal level, the SNR could be considered the same when we add ambient lighting as it is shown in Fig. 11. We can consider also that the ambient lighting has a weak effect on channel attenuation (Fig. 10) contrary to the precedent results presented in Fig. 4, 6 and 8. We can notice that these kind of characteristics is always obtained when semi- transparent PV modules are LiFi-optimized. Fig. 3 shows that this effect can be obtained without or with metallic grid. The particularity of this design is protected by a patent. We verify experimentally that modules present the same SNR when we are near a window when the sun shines. Now, we are doing further investigations to understand the physical phenomena and to improve the bandwidth of these kind of modules.

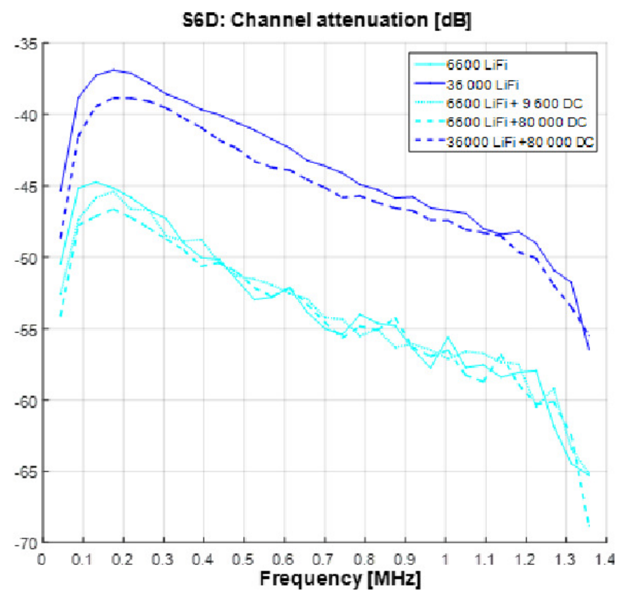


Fig. 10. Wysips® Crystal signal LiFi & DC responses

V. Conclusion

In this paper, we proove that we can design LiFi semi-transparent photovoltaic modules to obtain specific ambient lighting responses :

- conventional LiFi effects : the SNR decreases when the ambient lighting increases,
- unusual LiFi effects : the SNR increases when the ambient lighting increases,
- saturation stability effects : the SNR stays constant when the ambient lighting increases.

We show that the semi-transparent photovoltaic modules called Wysips® Crystal Connect solve two main great LiFi challenges: the integration of the receiver in mobile devices such as smartphones and the receiver ability to work in indoor and outdoor configurations in maintaining a constant data rate. Through this research, we designed specific semi-transparent modules optimized for LiFi application and we made a LiFi high-data rate LiFi demonstrator. The SunPartner high-data rate LiFi demonstrator using Wysips® Crystal Connect module

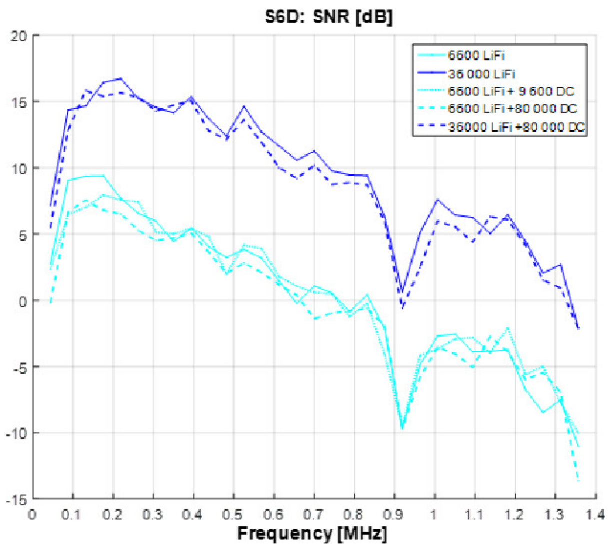


Fig. 11. Wysips®Crystal LiFi & DC responses

has been presented at MWC 2016. It allows streaming videos and maintain a constant data rate about 5 $Mbit/s$.

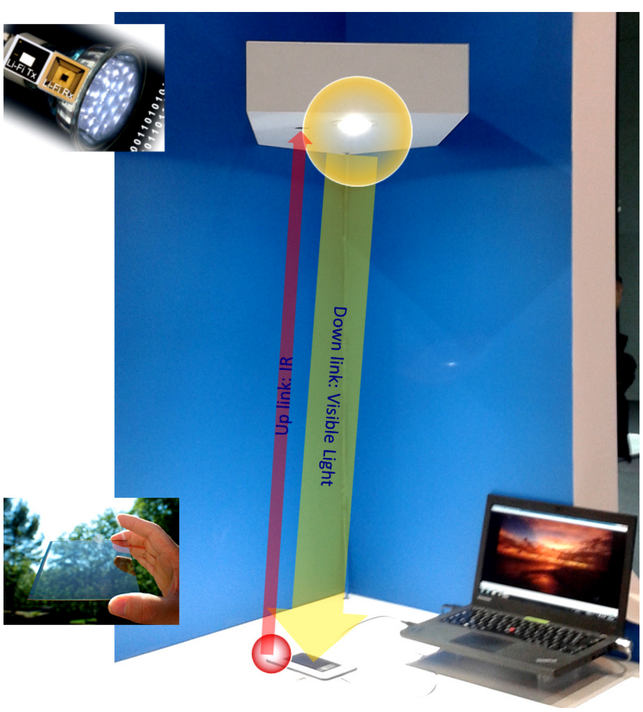


Fig. 12. SunPartner high-data rate LiFi Demonstrator

Acknowledgment

The author is grateful to the CEA Leti and in particular to Luc Maret (CEA Leti) for discussion about measurement investigations, simulation developments and fruitful discussions about the LiFi application.

References

[1] H. Haas, L. Yang, Y. Wang and C. Chen *What is LiFi?*, Journal of LightWave Technology, Vol. 34, Issue 6, 2015

[2] S.-M Kim and J.-S. Won, *Simultaneous reception of visible light communication and optical energy using solar cell*, International Conference on Convergence, 2013

[3] S. De Vechi, M. Bouchoucha, B Arrazat, B. Kerzabi, O. Gagliano and F. Aveline, *Wide and semi-transparent thin film silicon solar cell with very high fill factor for applications with displays*, PVTC, France: Aix-En-Provence, 2016.

[4] É. Bialic, L. Maret and D. Ktnénas, *Specific innovative semi-transparent solar cell for indoor and outdoor LiFi applications*, Applied Optics, Vol. 54, Issue 27, 2015