MODELLING OF THE CARRIER MOBILITY OF *LEUCAENA LEUCOCEPHALA* WOOD PLASTIC COMPOSITE (WPC) FOR THz PHOTOCONDUCTIVE ANTENNA

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Abstract— **Photoconductive antennas are most common devices used for generation and detection of Terahertz (THz) radiation and somehow have some similarity to the conversional RF/microwave antennas on the other hand, they also somehow different from the RF/microwave antennas in terms of the feeding technique. There are limitation on this antenna which is low efficiency and difficult to obtain high power. Study of the carrier mobility of photoconductive antenna substrate was significant to enhance antenna performance. This paper is aim to modelling carrier mobility of *Leucaena Leucocephala* Wood Plastic Composite (WPC) as photoconductive antenna substrate, using regression method and error bars within two samples with same density composition; 70% of polypropylene and 30% of *L. Leucocephala* filler Wood were analyzed. A simple model reproduces to predict the measured behavior.**

Keywords — photoconductive, carrier mobility, Leucaena Leucocephala Wood Plastic Composite (WPC)

I. INTRODUCTION

Terahertz (THz) frequency refers to region between millimeter and infrared band in electromagnetic spectrum, typically between 0.1 to 10THz [1]. There are many researches on milimeter wave and infrared band but limited study on terahertz band and the application but the potential applications including medical, chemical science, security, medical imaging and communication network [2]. Therefore it is necessary to enhance the THz radiation power from the photoconductive antenna by optimization design [3] but there is limited application have be release due to difficulties to generate high power signal for terahertz. Common method to generate THz is using laser and photoconductive antenna or material [1].

Photoconductive antenna is combination of the electrodes and supporting photoconductive (PC) material forms a key device for generating THz waves [1]. Typical photoconductive antenna consists of a semiconductor substrate, a dipole-shape electrode fabricated in the substrate and a bias voltage source connected to the electrodes [4]. However the major problem of the antenna and emitter is the very low optical-THz conversion efficiency to obtain high power THz waves [1,5]. Thus to enhanced the antenna performance proper evaluation of the photoconductive material conductance, carrier lifetime, carrier mobility [5,6] and increase the max bias voltage by the antenna's electrode is required [7].

Higher carrier mobility is also a desired character since it results in the high efficiency of THz wave generation [8]. It also has been the most important parameter to understanding the organic charge transportable materials and application of the optoelectronic device [9], especially when exploring new material as photoconductive antenna.

Paper and inject printing are most popular study organic material as antenna substrate studied by researcher, because of environmentally-friendly material, proposed approach to "green" radio frequency (RF) electronics and modules [10]. Many studies have been conducted using organic material and an antenna performance shown organic substrate have enough potential for being used as materials of substrate for planar antenna [11, 12].

This paper aimed to model carrier mobility of *L.Leucocephala* Wood Plastic Composite (WPC) as photoconductive antenna substrate, using fitting method and error bars within two samples with same density composition; 70% of polypropylene and 30% of *L.Leucocephala* filler Wood were analyzed. There are two sample refer to filler particle size 150μm and 500μm. Optimized compact model obtained from this study can be used as prediction allows other researchers to estimate the carrier mobility for next study.

Modelling carrier mobility for terahertz (THz) transmission become potentially useful for development of THz technologies and application such as antenna substrate for photoconductive antenna. Most common method for modulating THz transmission is using free carrier excitation in semiconductor or organic material excitation by electric or optical [13,14]. Therefore understanding the carrier mobility properties in these organic material is crucial importance to design and synthesize better materials and improve device performance [15] and mobility of carriers become importance parameter which effect directly the antenna performance [15-17].

II. PHOTOCONDUCTIVE ANTENNA AND CARRIER MOBILITY

For THz antennas, the substrate commonly build from semiconductor such as Si, InAs, ZnTe (crystal), GaSe, InP, and InGaAs due to the characteristic of materials. Different materials have difference mobility. To generate desired THz radiation, the substrate material have enough incoming laser power, a good PC material, an adequate bias voltage and a well-designed antenna namely in Table I [18- 19]. Table II is the summary of the properties of substrate material for difference materials based on research to achieve THz application.

TABLE I
THZ CHARACTERISTIC

Characterictic	Function
Ultra-short carrier lifetime	to get fast current pulses or CW current variation
Relatively high electron mobility	to get strong THz signals
High intrinsic resistivity and high breakdown voltage	to support applying high bias voltages)

TABLE II
SUMMARY MAIN PROPERTIES SUBSTRATE MATERIALS

Substrate Material	Carrier lifetime (ps)	Mobility (cm^2/Vs)	Resistivity (Ωcm)
GaAs [20]	2	3000	2
Ion-implanted GaAs [22]	0.2	2000	2
Be-doped LTG In GaAs [24]	0.35	1900	1.2×10^5
Fe-implanted In GaAs [25]	0.3	1500	1×10^3
ErAs:InGaAs [26]	0.2	490	3.4×10^2
Cold Fe-implanted InGaAsP [25]	0.3	400	1.2×10^3
LTG GaAs [21]	0.2	200	10^7
Be-doped LTG InGaAs [25]	1	100	7×10^2
ErAs:GaAs [23]	0.19	100	10^5

Different materials have difference mobility. Therefore it become something significant to study the carrier mobility of substrate material for photoconductive antenna because it can enchance THz radiation due to its increased maximum bias voltage [27]. Carrier mobility and the intensity of the static internal field also affect the amplitude and phase of the radiated THz field.

Organic material has limitation on lower transport state and many organic is π-conjugated material. The π-conjugated are carbon based macromolecules which have extended chains of alternating single and double bond $-(CH = CH)_n$. Therefore to enhance the potential of organic material can be done using doping process and composite with other material [28, 29].

III. MODELLING CARRIER MOBILITY

Modelling is an important tool which helps predict circuit element behavior before they are fabricated, saving resources, time and money. From the previous study, modelling carrier mobility can be done using simulation and numerical method. Numerical methods allow a more exact modelling of the physics involved during the various sequential processing steps [30].

Most of researchers using simulation by apply Monte Carlo method or simulation using Thomas-Fermi and Boltzmann transport. But Monte Carlo method, in which the Boltzmann equation is not directly solved, but the distribution function and the transport coefficients are evaluated by the simulation of electron trajectories using random numbers [31, 32].

The initial fitting method introduced by Spear based on ideal case of a perfectly nondispersive sample where a thin charge sheet moves through the sample at constant speed without any spreading [33]. Hall Effect data typical analysis is using least square fitting or trust region method [34]. Advantages of fitting method is can made prediction and assumption the data analysis.

IV. SAMPLE DETAILS

Carrier mobility of Wood Plastic Composite (WPC) sample composed of 70% of polypropylene and 30% of *L.Leucocephala* filler Wood were measured using Hall Effect measurement. This measurement is useful to determine various parameters such as Hall voltage (V_H), carrier mobility, carrier concentration (n), Hall coefficient (R_H), resistivity, magnetoresistance (R_B), and the carrier conductivity type (N or P).

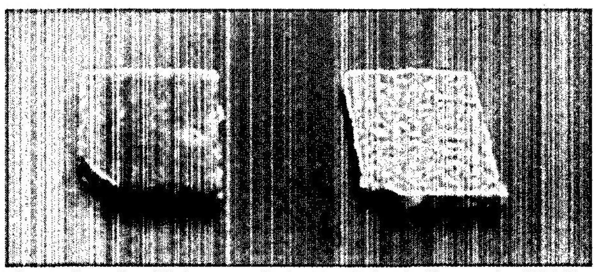

Fig. 1. Sample of *L.Leucocephala* Wood Plastic Composite (WPC)

This device setup integrates with Hall Effect measuring software given the carrier mobility and others parameters with the current is applied with constant injected temperature and magnetic field.

TABLE III
SAMPLE DETAILS INFORMATION

Sample	Temperature (K)	Magnetic field, B	Carrier Mobility (cm2/Vs)	Resistivity (Ωcm)
150μm	300	0.57T	5.31×10^3	10.8
500 μm			8.55×10^2	59.9

V. METHODOLOGY

Data analyzed using two techniques, which are error bars and least square method one of curve fitting technique. This is common way to made comparison data to a theory is to search for a theoretical curve that matches the data as closely as possible. Various least square fitting methods have been used over the years for analyzing variable field Hall data [34].

The advantages using least square method as a part of analysis to find linear relationship between variables by choose best line closet to the point on the scatterplot. Scatter diagrams are important for initial exploration of the relationship between two quantitative variables.

Meanwhile error bar analysis help to communicate the size of the difference between groups and to indicate instances where statistically significant differences exist and estimate the uncertainty after making multiple measurements. It normally used standard deviation; therefore data points will be outside of the error bars when assuming that the errors are normally distributed, which means that they are described by the bell-shaped curve or Gaussian shown in the discussion of standard deviation.

VI. Result And Discussion

Measurement data from two samples were analyzed and discuss. The two method of analysis of carrier mobility from the literature review will also be tested.

a) Hall Voltage

Summary of Hall voltage two samples shown in Table IV, where calculated refer to (1).

$$V_H = \frac{V_{13} + V_{24} + V_{31} + V_{42}}{8} \quad (1)$$

TABLE IV
SUMMARY HALL VOLTAGE

Current (nA)	Hall Voltage	
	150μm	500μm
4	-1471.640	-1431.710
8	-1312.080	-738.426
12	-69.339	27.135
16	852.145	831.896
20	1278.031	1304.300
24	1450.298	1371.919
28	1375.002	1369.936
Equation	$y = 0.0664x + 14$	$y = 0.0072x + 13$

The limitation of input current for Hall Effect measurement is 1nA – 20mA [28] depend on machine specification. The hall voltage has a different polarity for positive and negative charge carrier. This information used to study the details of conduction in semiconductors and other materials. Hall voltage has showed good linearity when current are increase and error bars for Fig 2 shown large amount of overlap that includes the mean values. There are no significant different between current and voltage.

The increasing the Hall Voltage have correlation with performance antenna efficiency [7, 36]. This variation in the bias voltage has more significant effect on the antenna efficiency as compared to antenna resistance [37], because if the bias voltage is zero there is no THz wave because free carriers are not accelerated.

This illustrates that, while the parameters of the model were determined by comparison with measured mobility data from the literature, the fit of the model to measured characteristics over transverse field, substrate bias, and to devices with varying substrate composite is very good.

Accurately predict to measured relationship of current and Hall voltage were summarized in Table IV. The model predicts that an increase in the voltage can improve THz power conversion efficiency of the device [37].

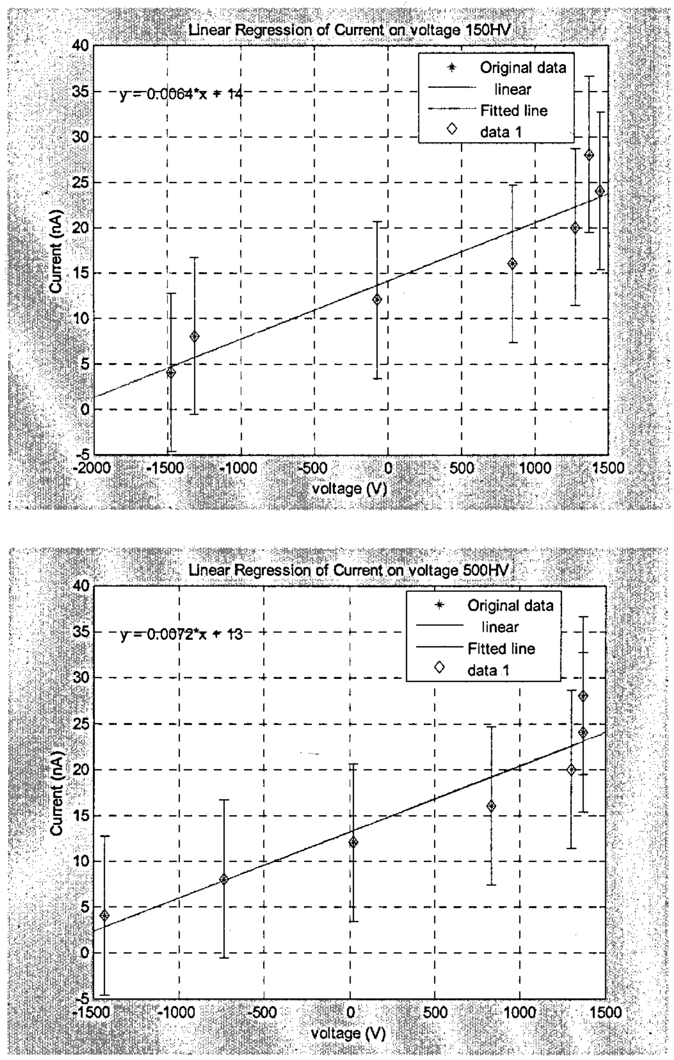

Fig. 2: The error in the I-V graph for 150μm and 500μm is determined using the best fit within the error bars.

b) Carrier Mobility

Another parameter in source conductance of the antenna is the carrier mobility and also desired characters to enhance high efficiency of THz wave generation [8]. In this subsection, the mobility of WPC sample dependent on the applied voltage and summary shown in Table V and IV. Result show carrier mobility for both sample reached maximum value at -1471.64V for 150μm and -1431.71V for 500 μm. However at higher voltage carrier mobility becomes lower due to saturate velocity.

The error bars on carrier mobility values are standard deviation for seven analyses on each sample and are a visual device that is generally used to convey uncertainty. The temperature and E- field dependence of the mobility is not taken into account. Error bars analysis shown linear amount of overlap that includes the mean carrier mobility therefore is not a significant differences between carrier mobility of *L.Leucocephala* for 150μm and 500μm particle size, shown in Figure 3 and detail in Table V and IV.

The mobility is studied as a function of composite and Hall voltage for different value of the particle size. It shown that carrier mobility increases when size of particle decreased, which is 150 μm has higher carrier mobility compared to 500 µm. It has potential to use as photoconductive antenna substrate material compared with other photoconductive material that has been studied by other researchers; 3×10^3 to 1×10^2 (refer Table IIV).

TABLE IIV
COMPARISON OF MAIN ELECTRICAL PROPERTIES OF DIFFERENT SUBSTRATE MATERIAL

Materials	Carrier Mobility (cm2/Vs)	Resistivity (Ωcm)
WPC 150µm	3.06×10^3	3.56×10^9
GaAs [20]	3000	2
Ion-implanted GaAs [22]	2000	2
Be-doped LTG In GaAs [24]	1900	1.2×10^5
Fe-implanted In GaAs [25]	1500	1×10^3
WPC 500µm	5.05×10^2	7.84×10^7
ErAs:InGaAs [26]	490	3.4×10^2
Cold Fe-implanted InGaAsP [25]	400	1.2×10^3
LTG GaAs [21]	200	10^7
Be-doped LTG InGaAs [25]	100	7×10^2
ErAs:GaAs [23]	100	10^5

The mobility is initially high at low composite because grains are fully depleted and traps are partially filled. Therefore it significant with research on composite material as antenna substrate for microstrip patch antenna using T_1O_2 with low density polyethylene (LDPE) presented the graded material substrate enhanced S11 parameter, bandwidth and directivity value high as compare to single composition substrate [31]

Carrier mobility of antenna substrate is importance study parameters to enhance THz radiation power and efficiency for photoconductive antenna since until now it is best device to generate THz waves.

TABLE V
SUMMARY OF CARRIER MOBILITY AND RESISTIVITY FOR SAMPLE 150µM

Hall Voltage (V_H)	Mobility (cm²/Vs)
-1471.640	3.06×10^3
-1312.080	5.39×10^{-2}
-69.339	6.65×10^1
852.145	6.76×10^2
1278.031	6.79×10^2
1450.298	1.63×10^1
1375.002	1.52×10^1
Equation	y=-0.46x+780

TABLE IV
SUMMARY OF CARRIER MOBILITY AND RESISTIVITY FOR SAMPLE 500µM

Hall Voltage (V_H)	Mobility (cm²/Vs)
-1431.710	5.05×10^2
-738.426	1.26×10^1
27.135	3.63×10^0
831.896	1.02×10^2
1304.300	1.84×10^2
1371.919	1.88×10^1
1369.936	1.93×10^1
Equation	$y = -0.089x + 160$

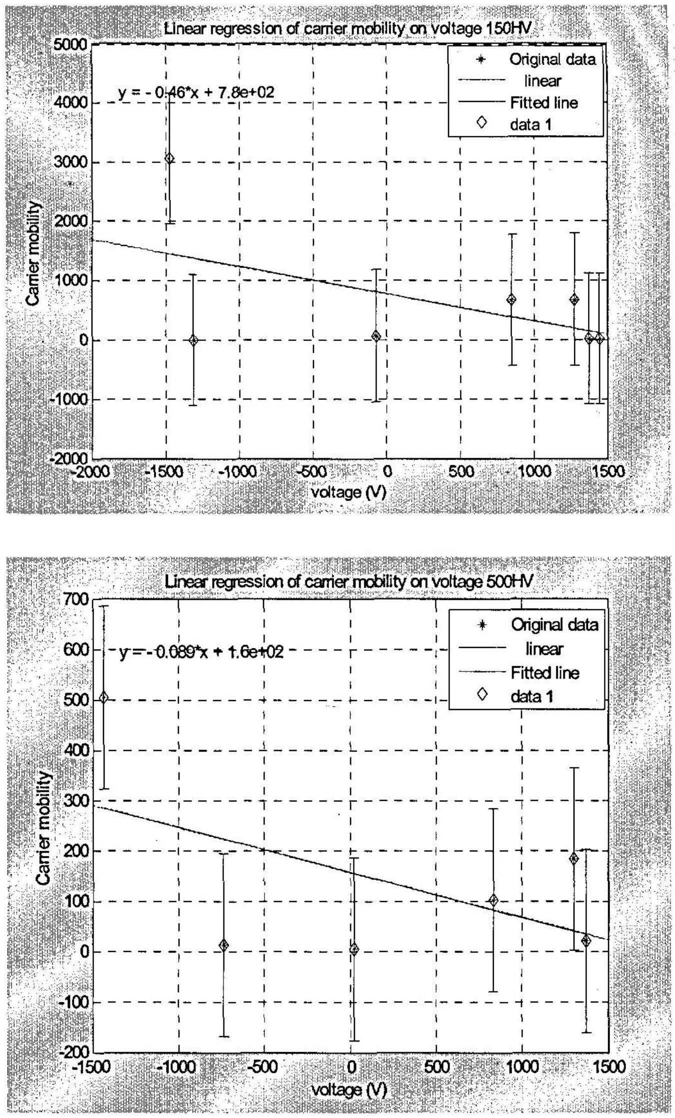

Fig. 3: Plot regression and error bars graph (standard deviation), the correlation between carrier mobility and Hall voltage for 150µm and 500µm

VII. CONCLUSION

Understanding photoconductive antenna is important to improve THz antenna efficiency and increase the power. In this paper we have modelling carrier mobility of sample composed of 70% of polypropylene and 30% of *L. Leucocephala* filler Wood with different particle size. These data together were obtained using Hall Effect measurement. The result show the *L.Leucocephala* Wood Plastic Composite (WPC) have potential to become PC material compare with other materials. WPC filler size, 150µm have higher carrier mobility other than 500µm. The carrier mobility were decrease as the hall voltage increases and have carrier saturated velocity. Finally, the above expressions have been implemented in prediction for next research. Studied on another important electrical parameters which is temperature, carrier lifetime and different concentration should be done on these sample in the future work to further strengthen these finding.

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