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4G Antennas and related SAR for wireless eyewear devices

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Abstract

In this paper, we first present a feasibility study to design 4G antennas (700-960MHz and 1.7-2.7GHz) for eyewear devices. Those eyewear devices should be connected to the last generation cellular networks, Wireless Local Area Networks or wireless hotspots. Three coupling element type antennas with their matching networks are evaluated in terms of reflection coefficient and total radiation efficiency when the eyewear is placed on the user's head. We also present Specific Absorption Rate (SAR) simulations when the eyewear is positioned over an homogeneous SAM phantom and over an heterogeneous VH (Visible Human) phantom: the SAR levels are compared to international limit values. In a second step, we present experimental results obtained with 3D printed eyewears and coupling elements etched on classical PCB substrate where the matching circuits are optimized close to the feeding point of the coupling element. Simulated and measured values are in very good agreement: 7 to 16% and 9 to 35% total efficiency are respectively obtained for the low and high frequency bands. However, simulated SAR values are somewhat higher than authorized levels with preoccupant high electromagnetic field distribution close to the eye of the user.

Introduction

During the past years, wireless devices like smartphones, watches, tablets, have been growing tremendously. Recently, a strong interest has emerged for eyewear devices. Every major company have on-going research and development on this topic, the most advanced being the Google Glass from Google company that have been already launched and recently stopped for being enhanced and to better understand the potential market of those devices [1]. Those first glasses are using the Bluetooth 4.0 and Wi-Fi 802.11b/g protocol standards at 2.4 GHz. The antenna component is placed along the ear of the user like in wireless Bluetooth headsets for smartphones [2, 3]. As the involved output power of the front-end-modules of the Bluetooth and WLAN transceivers are relatively low, Specific Absorption Rate (SAR) is not an issue to be checked [4, 5]. The majority of the users who already tried those glasses considered them as really ergonomic and excellent for daily usage but they also pointed out a strong limitation in terms of connectivity (only Bluetooth and WLAN standards): indeed the user should have his smartphone in close vicinity of the eyewear or he should be located in a wireless hotspot area. In this context, there is clearly a need for the second generation of smart glasses to be connected to the cellular network. Therefore, 4G antennas should be designed for this purpose and SAR aspect should be cautiously studied.

In this paper, we first present a feasibility study (based on [6]) to design 4G antennas (700-960MHz and 1.7-2.7GHz) for eyewear devices to be connected to the last generation cellular networks and Wireless Local Area Networks. Three coupling element type antennas with their matching networks are evaluated in terms of reflection coefficient and total radiation efficiency when the eyewear is placed on the user's head. We also present Specific Absorption Rate (SAR) simulations when the eyewear is positioned over an homogeneous SAM phantom and over an heterogeneous VH (Visible Human) phantom: the SAR levels are compared to international limit values. In a second step, we present experimental results obtained with 3D printed eyewears and coupling elements etched on classical PCB substrate where the matching circuits are optimized close to the feeding point of the coupling element. Simulated SAR values are also given for these optimized prototypes.

1. Feasibility study

1.1. Design of antenna concepts

It is extremely challenging to design a 4G dual-wideband antenna (30 and 45% bandwidth respectively for 700-960MHz and 1.7-2.7GHz) considering the small space available in the eyewear platform. As the free space wavelength at 700 MHz is larger than the allocated space for the antenna (42.8cm versus 2-3 cm), a resonant antenna is absolutely not the adequate choice. We propose to use a coupling element to excite currents over the Printed Circuit Board (PCB) of the eyewear aiming at lower radiation quality factor than a resonant antenna and therefore potentially higher radiation bandwidth [7]. A coupling element is fed like monopole but it is optimized to efficiently excite the currents of a metallic body (here the ground plane of the eyewear PCB). The input impedance of the coupling element is then adjusted to the desired value, 50Ω here, with the help of an optimized matching circuit. The PCB we choose is shown in Fig. 1: realistic dimensions have been extracted from [1].

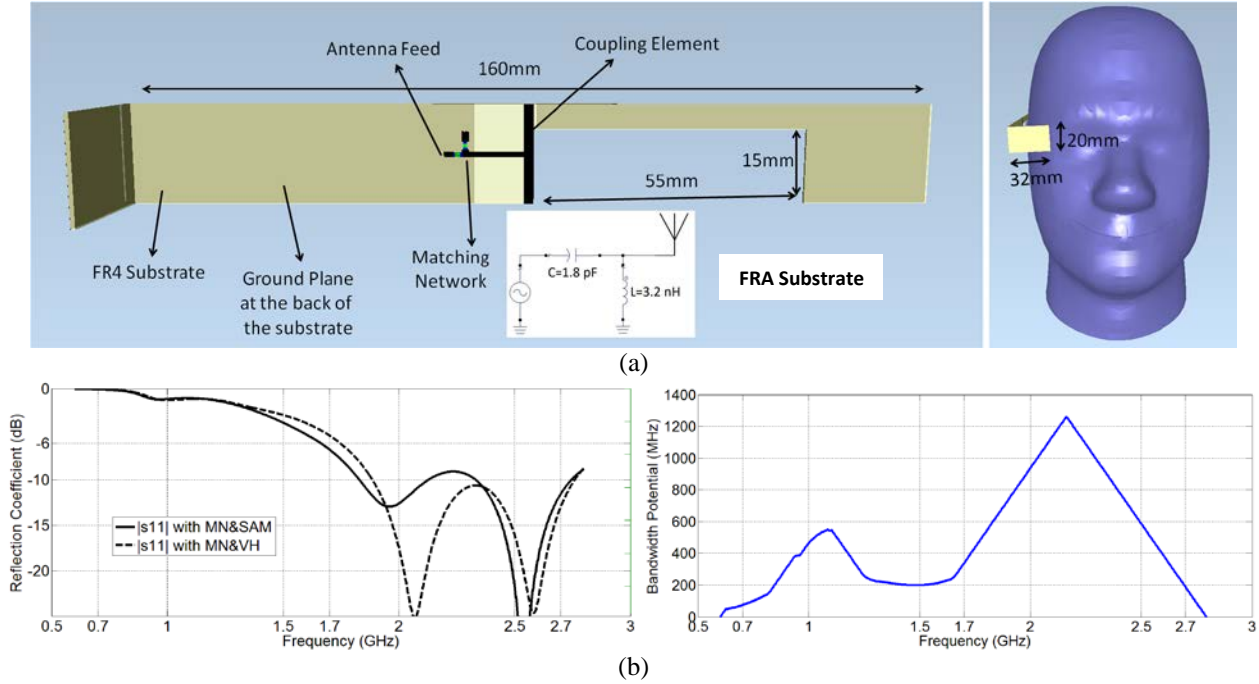


Fig. 1- (a) Prototype 1 optimized with SAM head

(b) Simulation results (reflection coefficient and bandwidth potential) for prototype 1 with SAM and VH heads

It should be specified at this stage that we considered plastic eyewear only as opposed to metallic ones. However, it has been demonstrated in [8,9] that a metallic frame has non negligible effects upon the antenna performance and SAR values. We sequentially achieved our simulations with the SAM and VH heads. The total dimensions of the FR4 PCB have been set to $160 \times 20 \times 0.8 \text{ mm}^3$ (see Fig. 1a) with a perpendicular part in front of the eye ($32 \times 20 \times 0.8 \text{ mm}^3$) and a metallic-less part around the ear of the user ($55 \times 15 \times 0.8 \text{ mm}^3$). Our analysis of the shape of this structure led us to consider three potential positions for the integration of an efficient capacitive coupling element. The first one consists in placing the coupling element in the middle of the long portion of the PCB that is in front of the ear. The coupling element we optimized is a simple metallic strip having a width of 2mm, printed on the inner surface of the PCB (in front of the SAM phantom). Electromagnetic simulations have been conducted with EMPIRE Xcel 6.01 software. The bandwidth potential has been obtained with Optenni Lab software [10] considering a 2-component matching network and a reflection coefficient lower than -6dB. The blue curve in Fig. 1b is obtained as follows: for every frequency point, Optenni software tries several topology of matching networks (with optimized component values) to satisfy the criterion we specified ($|\text{reflection coefficient}| < -6\text{dB}$) considering the simulated input impedance of the coupling element as its input data. The best matching network circuit is kept (highest frequency bandwidth) and the bandwidth potential value is given at this frequency point. This bandwidth potential reveals the frequency bandwidth we should get from this "Coupling Element+Matching Network" considering a reflection coefficient lower than -6dB.

To satisfy our matching goal, the bandwidth potential should be 260 MHz centered at 830 MHz and 1 GHz centered at 2.2 GHz. In Fig. 1b, the bandwidth potential is sufficient to cover the high band (higher than 1 GHz) but the low band (700-960 MHz) is not covered. This is mainly due to the fact that the position of the coupling element is not optimal for the excitation of the currents flowing over the PCB. However, we indeed decided to optimize a matching circuit with a shunt inductor (found to be 3.2 nH) and a series capacitor (found to be 1.8 pF) to operate in the 1.7-2.7 GHz band with a reflection coefficient lower than -6dB. In Fig. 1b, it can be seen that not so much differences exist between the simulated reflection coefficient with SAM head and the reflection coefficient with VH head. The simulated radiation efficiency which takes into account the losses in the head ranges from 20 to 25% in the frequency band of interest.

In prototype 2, the coupling element was placed behind the ear (Fig. 2a). The obtained bandwidth potential in low and high bands is definitely higher than the ones obtained with prototype 1 (Fig. 2b). PCB currents are definitely better excited with this coupling element position as we can benefit from all the length of the available PCB. With a 2-component matching network (shunt inductor of 14nH and series capacitor of 1.6pF), a dual-band behavior is obtained to ensure operation in the 700-960 MHz and 1.7-2.7 GHz frequency bands with a reflection coefficient lower than -6dB. As before, it can be seen that not so much differences exist for the reflection coefficient if we compare the simulated curves with SAM and VH heads. In average, simulated radiation efficiencies are 9% in low band and 20% in high band.

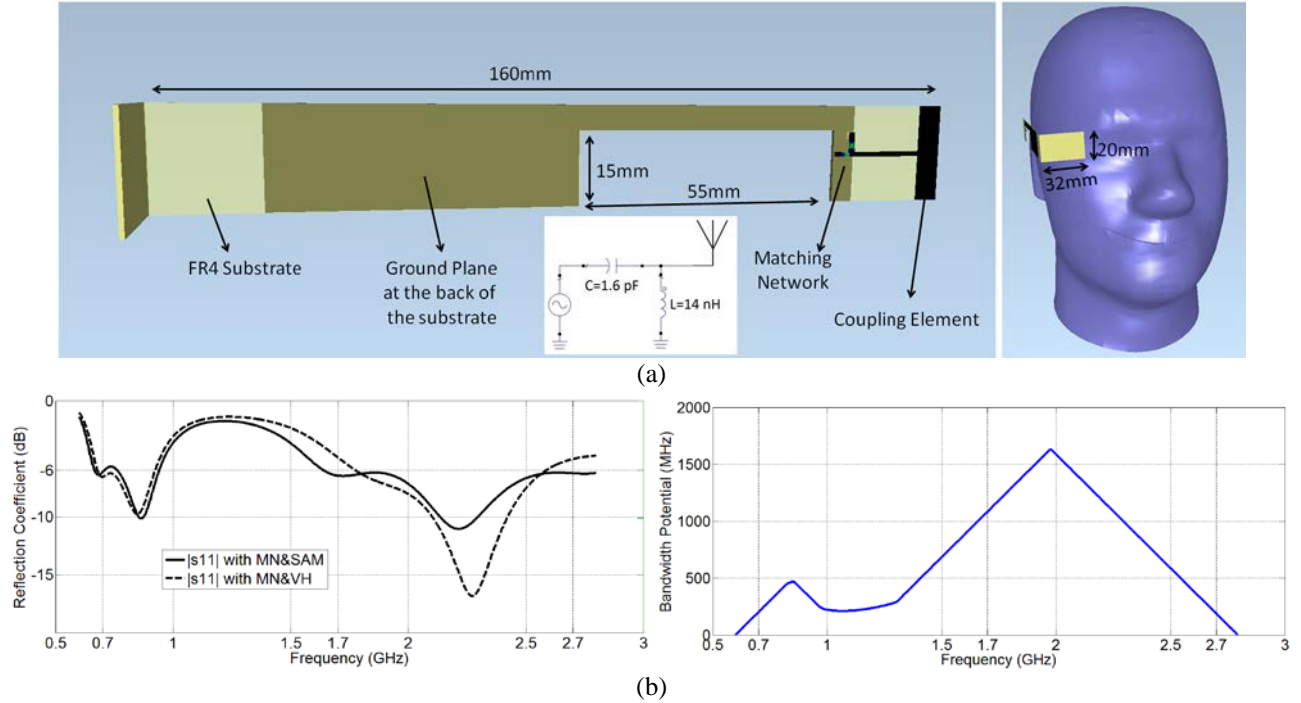


Fig. 2- (a) Prototype 2 optimized with SAM head
(b) Simulation results (reflection coefficient and bandwidth potential) for prototype 2 with SAM and VH heads

The coupling element from prototype 3 is placed at the end of the frame, in front of the eye (Fig. 3a). Dual-band coverage is obtained with a 3-component matching network (2 series inductors being 8 and 12 nH and a shunt capacitor being 0.2pF). It can be seen again that not so much differences exist for the reflection coefficient if we compare the simulated curves with SAM and VH heads. In average, simulated radiation efficiencies are 14% in low band and 36% in high band.

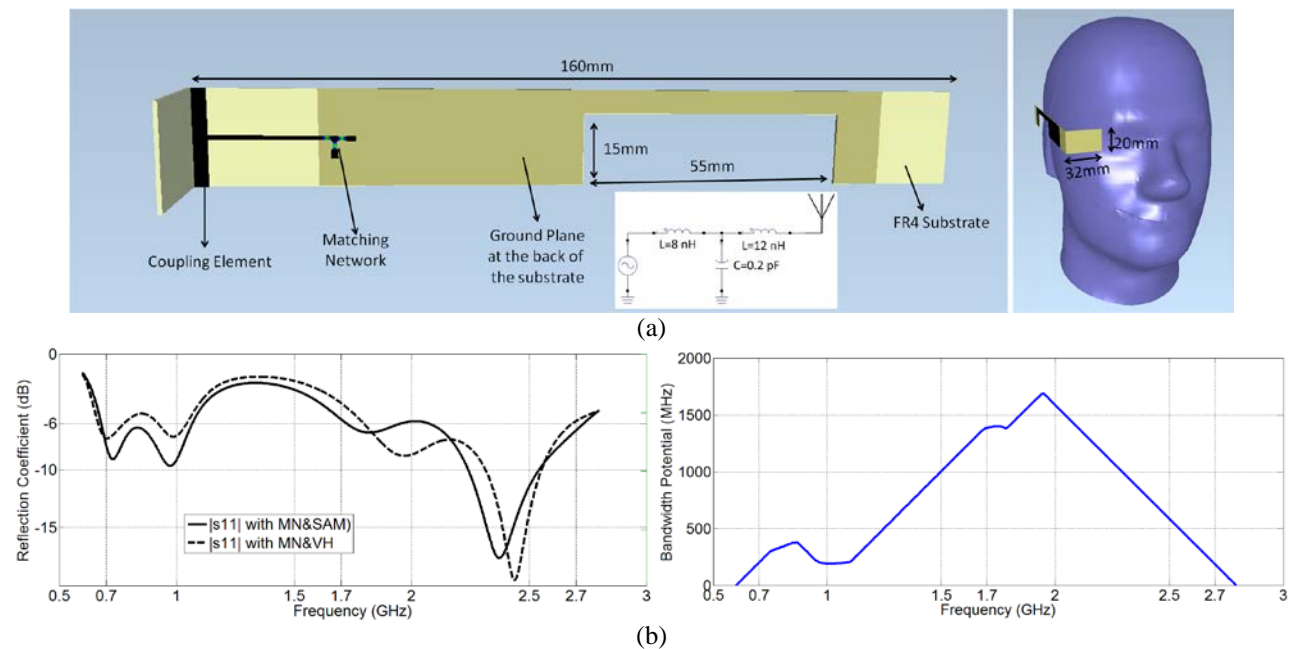


Fig. 3- (a) Prototype 3 optimized with SAM head
(b) Simulation results (reflection coefficient and bandwidth potential) for prototype 3 with SAM and VH heads

3D radiation patterns of all three prototypes are shown in Fig. 4 at 800 MHz and 2.2 GHz. All antennas tend to radiate in a perpendicular direction of their coupling elements, away from the user's head as it is usually the case in smartphones. However, it is of paramount importance to simulate the SAR levels generated in SAM and VH heads.

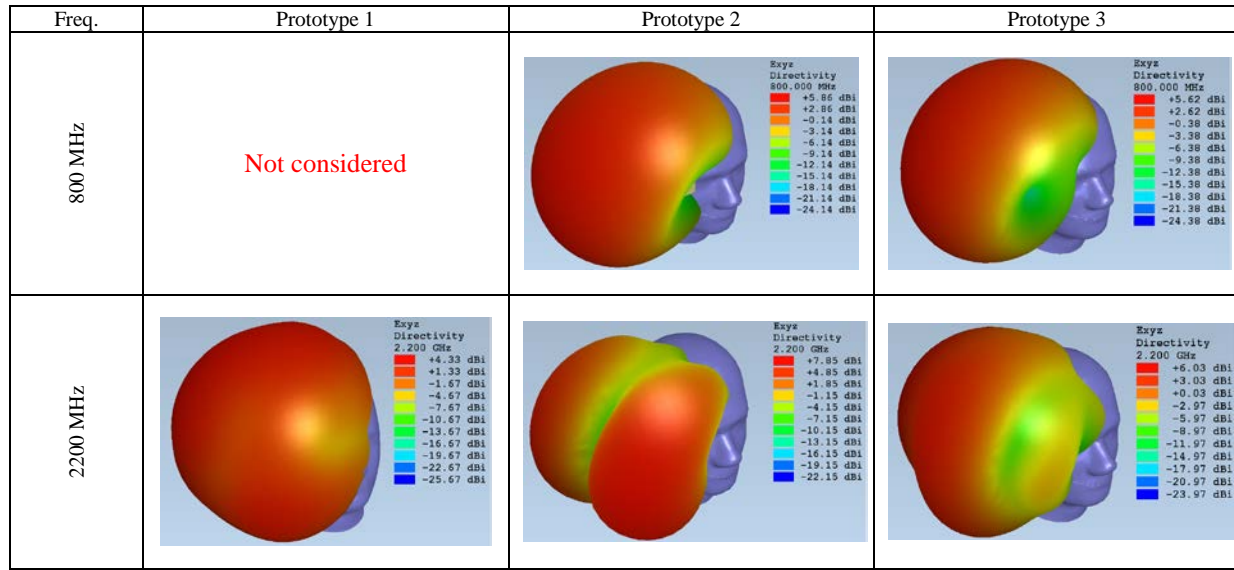


Fig. 4- Simulated radiation patterns at 800 MHz and 2.2 GHz for all three prototypes

1.2. SAR Simulations

During the past twenty years, there has been a strong public and scientific interest for possible **harms** of radiated electromagnetic waves by mobile phones. The transmitted power by a mobile phone is therefore accurately regulated to limit the absorbed power levels by the user's head. The main characteristic to evaluate the interaction with the user is the SAR: RF power absorbed by a unit mass of tissue (W/kg). Two international limits exist: one in Europe (SAR limited to 2W/kg averaged over 10g during 6min.) [11] and one in USA (SAR limited to 1.6W/kg averaged over 1g during 30m [12]). Lots of papers have simulated SAR levels in the user's head originated by a mobile phone when positioned close to homogeneous SAM or heterogeneous VH head phantoms [13, 14]. The averaged SAR over 1g is typically twice the SAR averaged over 10g. SAM head usually creates higher SAR values than VH. It is well established that the SAR level created by a mobile phone depends on the transmitted frequency, the distance of the electromagnetic source from the head and the antenna-type. The SAR value in homogeneous phantom exponentially decreases as we move away from the source. This is more complicated for a real (heterogeneous) head because this last one is composed of several tissue layers, each having different dielectric properties. This layer arrangement creates discontinuities at their interface and sometime resonances in some body parts or organs like the eye for instance: electric fields increase (instead of decreasing, as expected) as we move away from the source. For example, if we expose the eyes to a certain amount of power, the SAR value in the eyes could be twice the SAR value in neighbor tissues specifically at frequencies like 600 MHz and 2.4 GHz [9, 15, 16]. It has been also shown that the metallic frames of an eyewear could act as passive scatters and SAR values in the eyes could significantly increase in this specific case [9].

In this paper, every simulated SAR value have been given for a normalized 0.25W incident power [14] but it should be mentioned that incident power in the GSM1800 band should be normalized to 0.125W if we want to be realistic.

1.2.1 SAM Phantom

Simulated SAR values when the eyewear is placed over a SAM phantom are given in Table I. They are normalized to incident power of 0.25W and accepted power of 0.25W (matching not taken into account at the input port in this last case). Liquids with different dielectric properties at different frequencies have been used: $\epsilon_r = 41.5$; $\tan\delta = 0.467$ at 835 MHz and $\epsilon_r = 39.2$; $\tan\delta = 0.337$ at 2500MHz. SAR levels which are above the limits are set in bold italic letters in Table I. The proximity of the source and the absence of shielding ground plane toward the head are leading to SAR values which are globally much higher than the ones obtained with generic smartphones. It should be also noted that the obtained radiation efficiencies with our prototypes (10-15% in low band and 20-35% in high band) are largely higher than the ones usually encountered with modern smartphones (radiating with head and hand): 5% in low band and 15% in high band. The 1g SAR is always above 1.6W/kg but simulated values seems to be more acceptable for the 10g SAR 2W/kg limit: they are always higher than the limit in low band (except prototype 1 at 2200 MHz). With prototype 3, SAR values are always lower than the SAR values from the other prototypes because the source is placed further away from the head.

TABLE I : SIMULATED SAR VALUES WITH SAM PHANTOM (W/KG)

		0.25W Incident Power		0.25W Accepted Power (without S_{11})	
Prototype	Freq. (MHz)	1g SAR	10g SAR	1g SAR	10g SAR
1	1900	<i>7.86</i>	<i>3.32</i>	<i>8.37</i>	<i>3.53</i>
1	2200	<i>4.31</i>	<i>2.07</i>	<i>4.88</i>	<i>2.35</i>
1	2500	<i>4.36</i>	1.54	<i>4.39</i>	1.55
2	835	<i>4.33</i>	<i>2.08</i>	<i>4.96</i>	<i>2.39</i>
2	1900	<i>2.97</i>	1.47	<i>3.89</i>	1.92
2	2200	<i>4.18</i>	1.99	<i>4.54</i>	<i>2.16</i>
2	2500	<i>3.68</i>	1.83	<i>4.69</i>	<i>2.33</i>
3	835	<i>4.17</i>	<i>2.03</i>	<i>5.50</i>	<i>2.68</i>
3	1900	<i>2.47</i>	1.18	<i>3.19</i>	1.53
3	2200	<i>2.22</i>	1.04	<i>2.60</i>	1.22
3	2500	<i>1.96</i>	0.82	<i>2.11</i>	0.89

1.2.1 VH Phantom

Simulated SAR levels with VH phantom are given in Table II. The characteristics of the VH tissues simulated with EMPIRE XCcel are dispersive which means that they are automatically adjusted by the software when frequency sweeps. The obtained SAR values are close to the ones obtained with the SAM head. Especially, the 1g SAR values are always higher than 1.6 W/kg but lower than 2W/kg for the 10g SAR limit. It should be noted that the heterogeneous VH head has an external geometry which is different from the SAM head and therefore, the source/head distance is slightly different from one case to another. Except for prototype 3 at 2500 MHz, SAR values for VH head are always lower than SAR values obtained with SAM head. In our simulation, an interesting phenomenon was observed: the metallic part of the PCB which faces the eye induces an electromagnetic surface wave which propagates in the tissues around the eye. Several SAR distributions are shown for all prototypes (Fig. 5): the maximum SAR always appears on the side of the head with some worrying secondary spots around the eye, especially for prototype 1 and 3.

TABLE II : SIMULATED SAR VALUES WITH VH PHANTOM (W/KG)

			0.25W Incident Power		0.25W Accepted Power (without S_{11})	
Prototype	Freq. (MHz)	Eff. (%)	1g SAR	10g SAR	1g SAR	10g SAR
1	1900	25.2	<i>3.53</i>	1.64	<i>3.86</i>	1.79
1	2200	36.0	<i>2.90</i>	1.32	<i>3.04</i>	1.38
1	2500	42.1	<i>1.80</i>	0.85	<i>1.84</i>	0.87
2	835	10.0	1.50	0.97	<i>1.69</i>	1.09
2	1900	19.8	<i>1.64</i>	0.83	<i>2.03</i>	1.03
2	2200	21.2	<i>2.25</i>	1.09	<i>2.35</i>	1.14
2	2500	20.9	<i>2.51</i>	1.14	<i>3.04</i>	1.38
3	835	12.7	<i>1.32</i>	0.80	<i>1.88</i>	1.14
3	1900	38.0	<i>2.40</i>	0.91	<i>2.83</i>	1.07
3	2200	33.3	<i>2.32</i>	1.00	<i>2.82</i>	1.21
3	2500	37.2	<i>2.62</i>	1.01	<i>2.73</i>	1.05

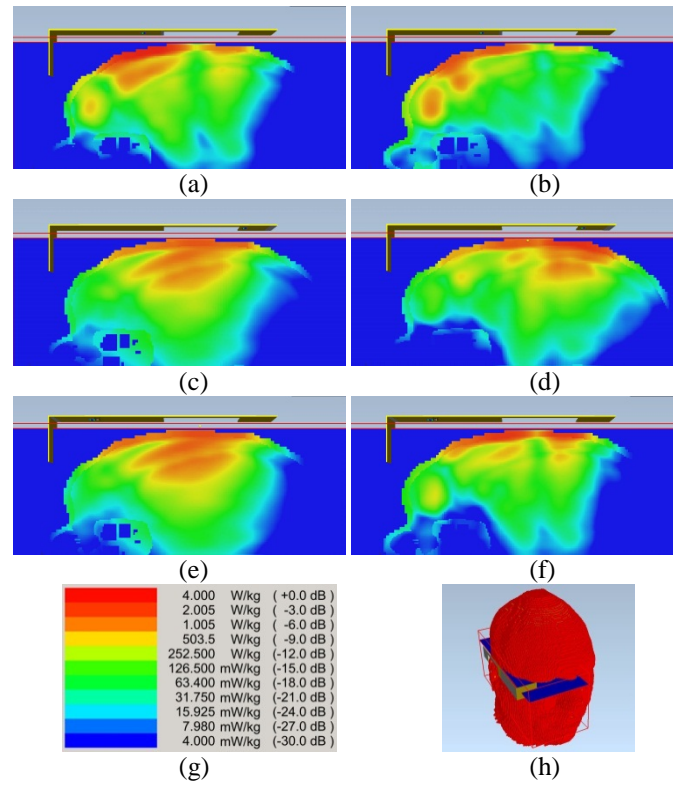


Fig. 5- 1g SAR distribution simulated for VH (a) Prototype 1 at 1900MHz; (b) Prototype 1 at 2500MHz; (c) Prototype 2 at 835MHz; (d) Prototype 2 at 2500MHz; (e) Prototype 3 at 835MHz and (f) Prototype 3 at 2500MHz. (g) Scale used for every SAR distribution; (h) Horizontal plane in the VH head where the SAR distributions have been extracted.

1.3 Conclusion on the feasibility study

In this feasibility study, we presented three possible locations for the antennas of 4G wireless eyewear devices operating in the 700-960 MHz and 1.7-2.7 GHz frequency bands. Very good radiation efficiencies have been obtained (10-15% at 835 MHz and 20-35% in high band). In general, SAR values in the head are always higher than the 1g limit but lower than the 10g limit if the considered input power is set to 0.25W. For some prototypes (and some frequencies), SAR peaks are observed in the eye of the user. This feasibility study validates our approach and we decided to further push our investigations in order to fabricate several prototypes of 3D printed 4G wireless eyewear.

2 Fabricated prototypes

The next step consisted of designing and fabricating realistic eyewears and PCBs. We first selected a standard fabrication process for the PCB where the coupling element is simply printed and the components of the matching network are soldered close to the feeding point of the coupling element. An Eyewear design, where one of the branch is replaced by a plastic opening where the PCB can fit have been developed and fabricated with a 3D printer from ABS plastic material ($\epsilon_r=2.97$, $\delta_{loss}=0.029$). The main idea was to use fast and cheap prototyping techniques. The designed model is presented in Fig. 6. Three holes have been left along the outside part of the ABS branch to let pass the WFL cable (Fig. 7). Three prototypes have been optimized, two of them being very similar to Prototype 2 and 3 previously presented in the feasibility study of this paper. A third mono-band prototype has been designed where the antenna exhibits a reflection coefficient lower than -6dB from 700 MHz to 2.7 GHz. In Fig. 8, Dr Will Whittow wears the plastic eyewear whereas Fig. 9 shows those eyewears placed over a SAM phantom. Three use-cases have been considered: eyewear on the user's head (antenna performances are optimized for this use-case), eyewear on the user's head and finger of the hand touching the touchpad (Fig. 10), eyewear in free space (Fig. 11a). The reflection coefficient and radiation pattern measurements have been conducted for two of those use-cases (Fig. 11a&b), in a SATIMO chamber.

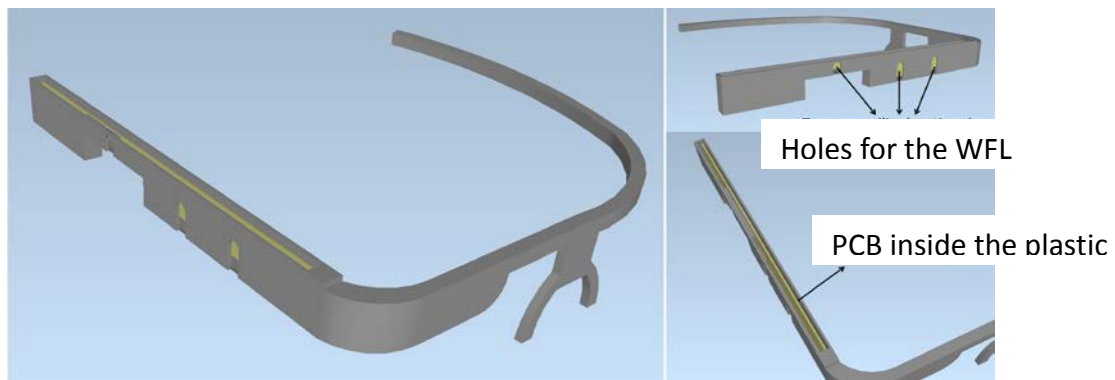


Fig. 6- Simulation model for the 4G wireless eyewear



Fig. 7- Fabricated eyewear with a 3D printer



Fig. 8- Eyewear mock-up on real user's head

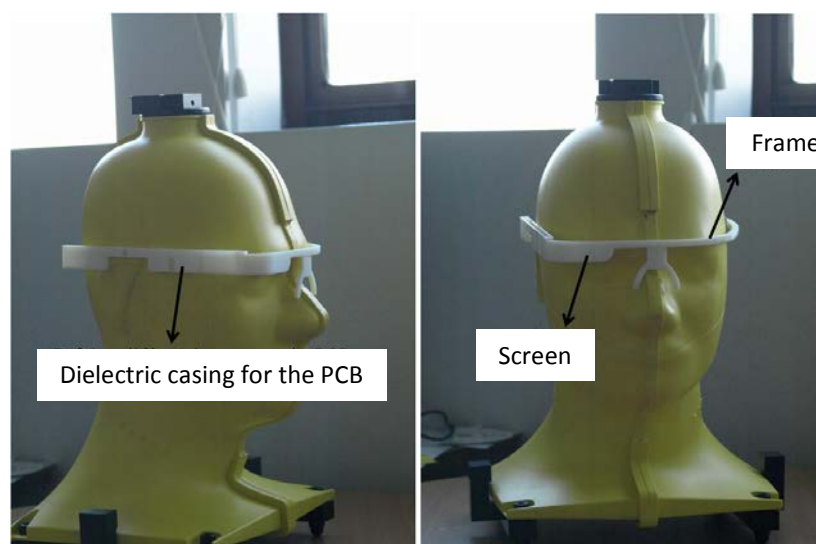


Fig. 9- Eyewear on SAM phantom

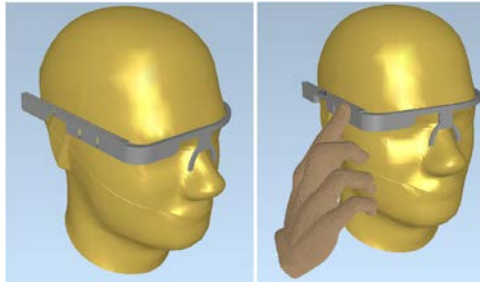
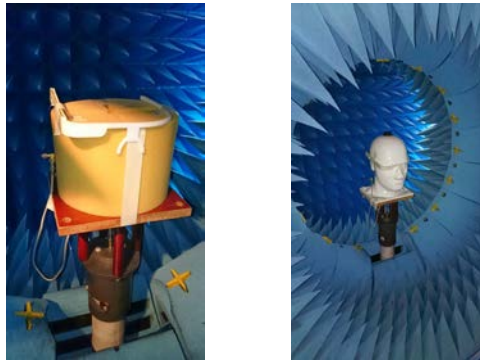


Fig. 10- Eyewear on the SAM phantom for the principal use-case and when the finger is positioned on the touchpad



(a)
(b)

Fig. 11- Eyewear placed in a SATIMO facility for reflection coefficient and radiation pattern measurements
(a) Eyewear over a foam support for free-space use
(b) Eyewear over a SAM head (principal use-case)

Prototype 2 has been optimized placing the coupling element close to the eye, with a 3-component matching network to cover the 700-960 MHz and the 1.7-2.7 GHz frequency bands (Fig. 12). The effect of the finger of the hand of the user over the reflection coefficient can be seen in Fig. 13: it is not negligible in the high band because the finger is placed in the vicinity of the coupling element.

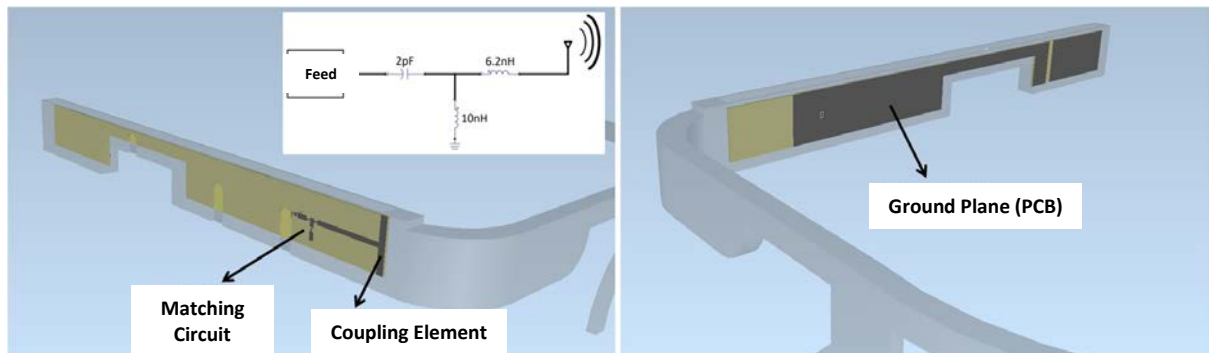


Fig. 12- Prototype 2

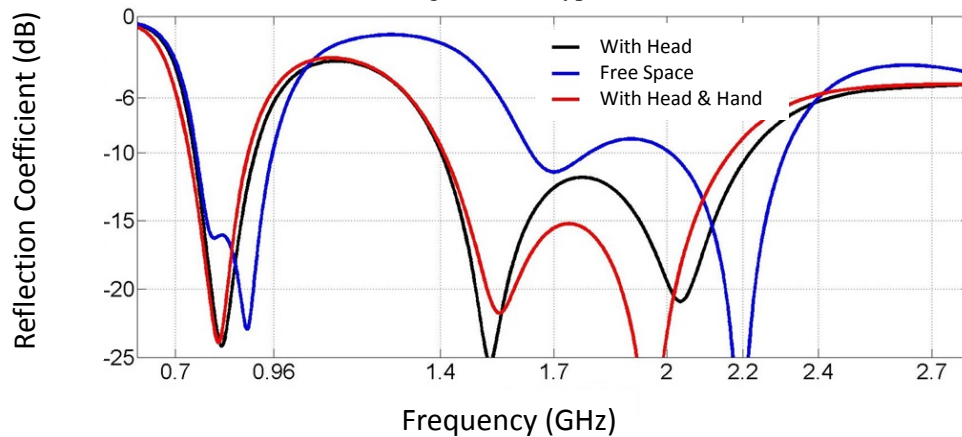


Fig. 13- Reflection Coefficient of Prototype 2 for all three use-case

The fabricated PCB is presented in Fig. 14 with ground plane facing (matching network and WFL connector are placed on the other side of the PCB). Simulated and measured reflection coefficients with SAM head are presented in Fig. 15. The agreement is fair but the two curves disagree above 2.2 GHz. This difference between simulation and measurement above 2.2GHz is believed to be due to the frequency dependent electrical properties of the head liquid, which were modeled as average values ($\epsilon_r = 40.5$ and $\tan \delta = 0.367$) in the target band for the time-domain simulations. The efficiency curves in free space and with the SAM head are presented in Fig. 16. With SAM head, the efficiencies range from 9 to 15% in low band and 20 to 35% in high band, showing also a good compliance with simulations.



Fig. 14- PCB for Prototype 2

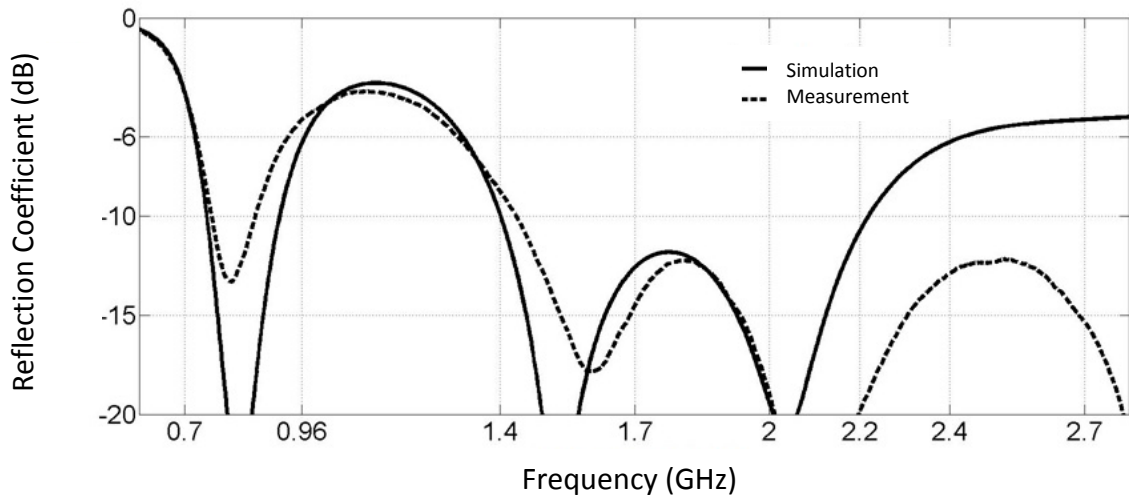
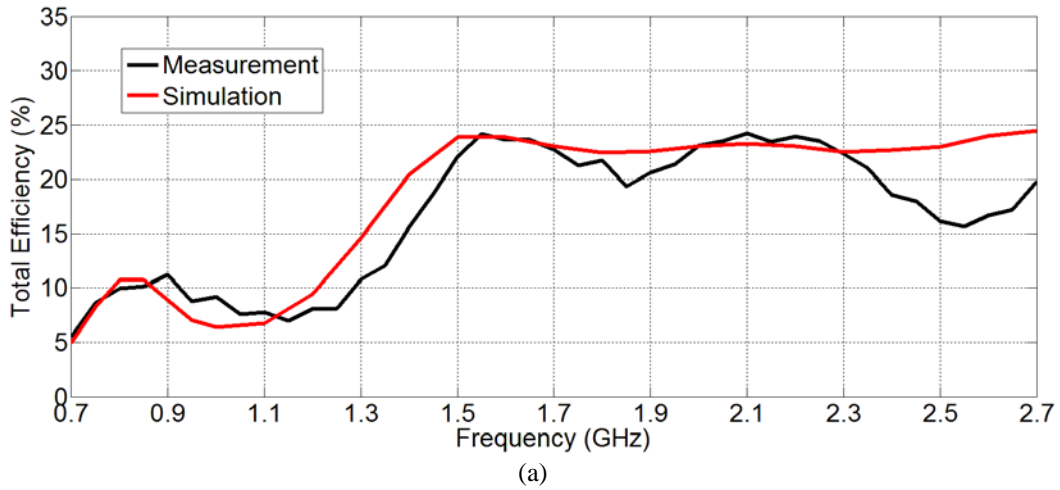
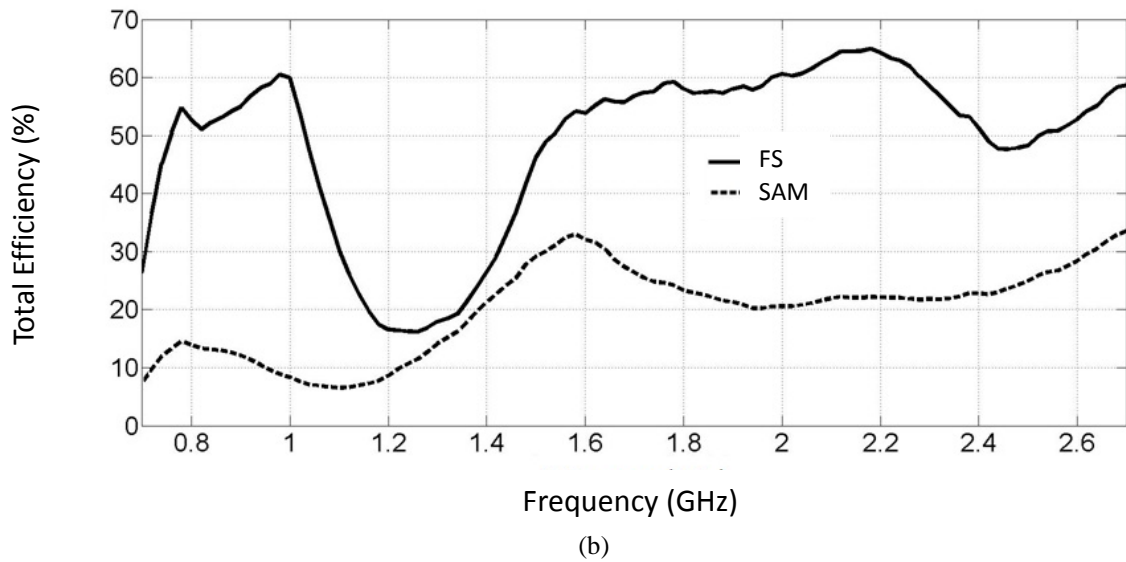


Fig. 15- Simulated and measured reflection coefficient of Prototype 2 with SAM head





(b)
Fig. 16- (a) Comparison of simulated and measured efficiency with SAM head (b) Measured efficiency for Prototype 2 in free space (FS) and with SAM head (SAM)

Prototype 3 has been optimized when placing the coupling element between the ear and the eye with a 3-component matching network to cover the 700-960 MHz and 1.7-2.7 GHz frequency bands (Fig. 17). The effect of the finger upon the reflection coefficient can be seen in Fig. 18. It is almost negligible in the high band. Simulated and measured reflection coefficient with SAM head are presented in Fig. 19. The agreement is fair but the two curves disagree above 2.2 GHz due to the frequency dependent electrical properties of the head liquid in reality. The efficiency curves in free space and with the SAM head are presented in Fig. 20. With SAM head, the efficiencies range from 7 to 12% in low band and 9 to 18% in high band.

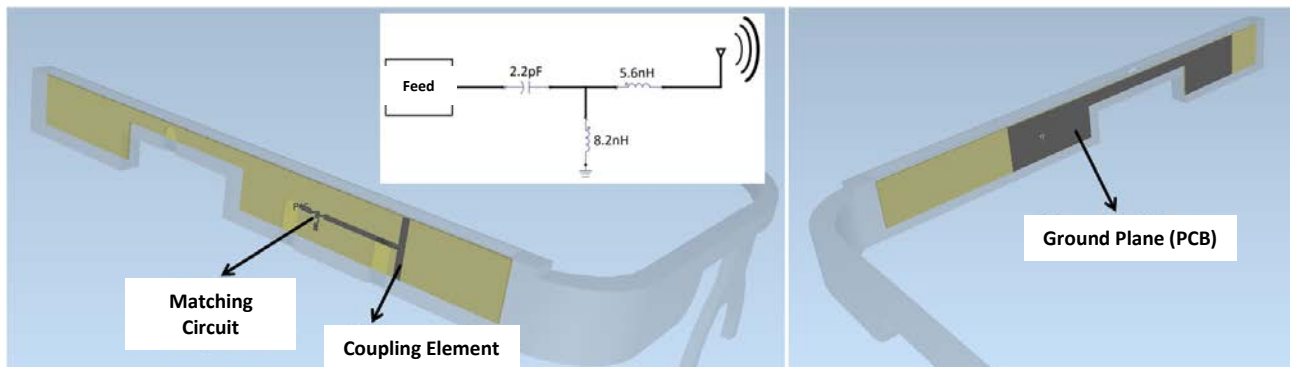


Fig. 17- Prototype 3

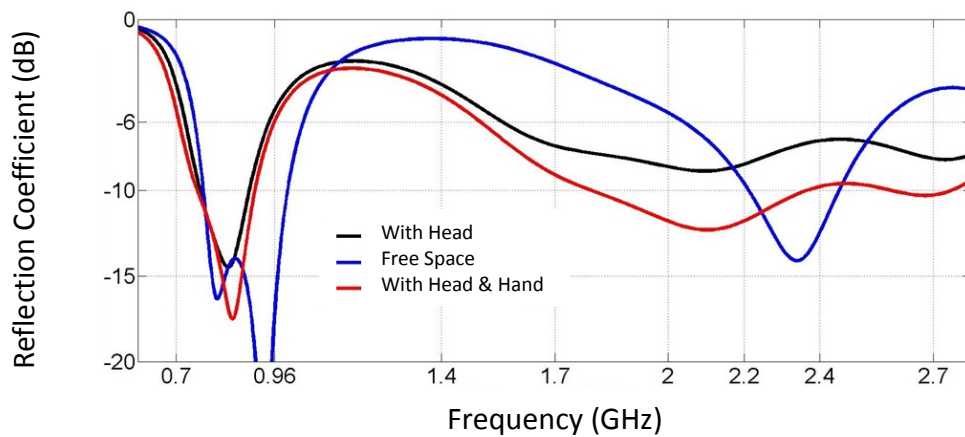


Fig. 18- Reflection Coefficient of Prototype 3 for all three use-case

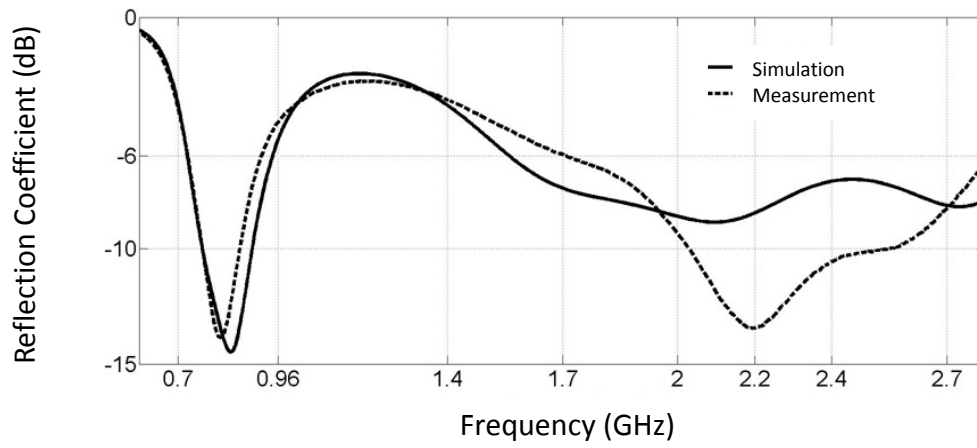


Fig. 19- Simulated and measured reflection coefficient of Prototype 3 with SAM head

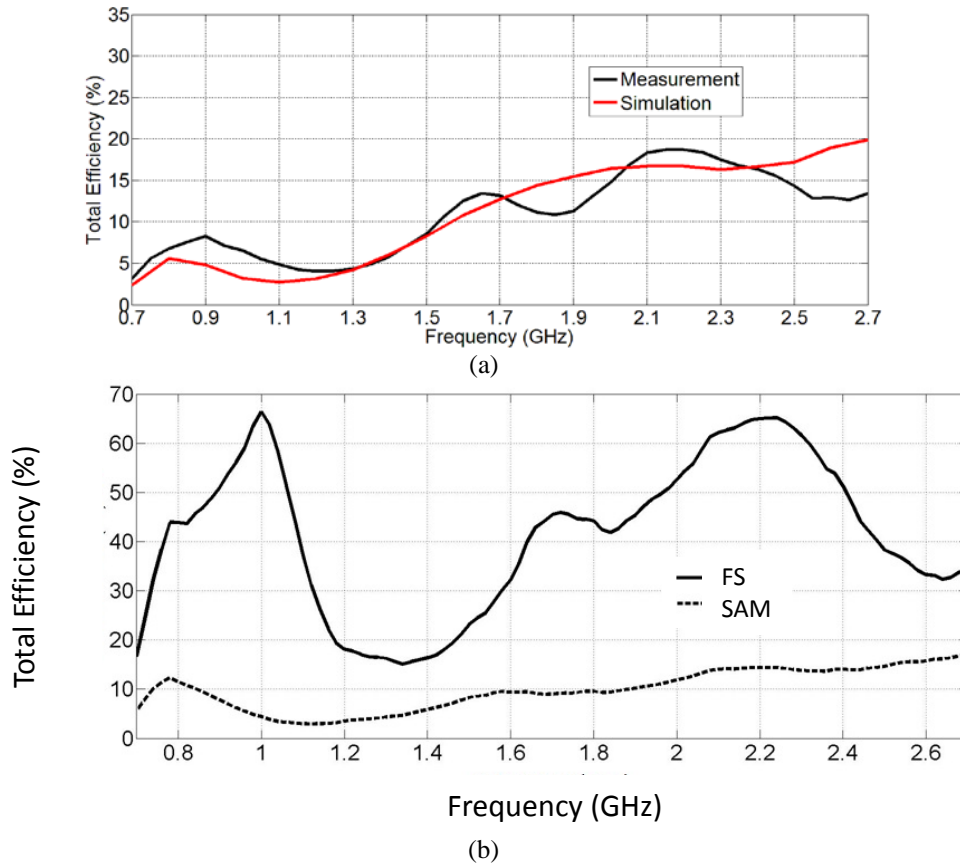


Fig. 20- (a) Comparison of simulated and measured efficiency with SAM head (b) Measured efficiency for Prototype 3 in free space (FS) and with SAM head (SAM)

Novel mono-band prototype 1 has been optimized placing the coupling element behind the ear with a 3-component matching network to operate continuously from 700 to 2700 MHz (Fig. 21). The effect of the finger of the hand of the user upon the reflection coefficient is shown in Fig. 22. The fabricated PCB is shown in Fig. 23, where the coupling element is shown with its matching network and the very small WFL connector. Simulated and measured reflection coefficients with SAM head are presented in Fig. 24. The agreement is fair but the two curves disagree above 2.2 GHz. The efficiency curves in free space and with the SAM head are presented in Fig. 25. With SAM head, the efficiencies range from 15 to 16% in low band and 16 to 21% in high band.

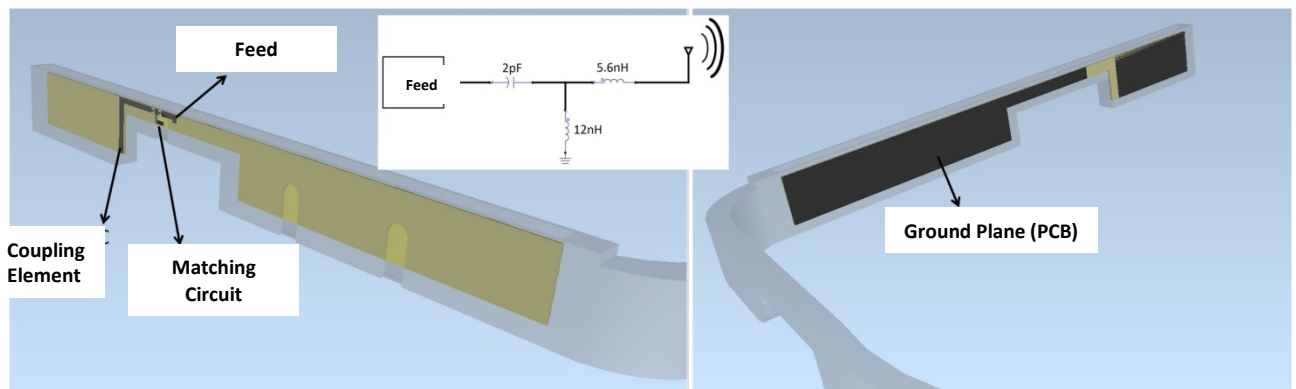


Fig. 21- Prototype 1

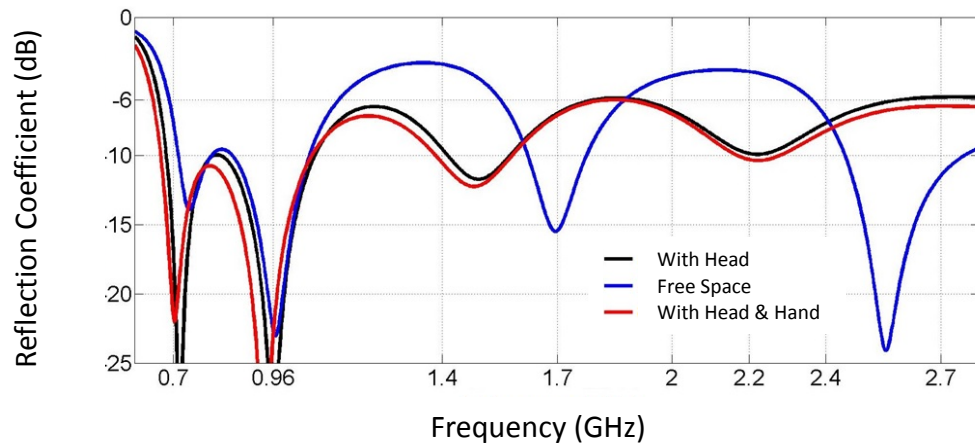


Fig. 22 - Reflection Coefficient of Prototype 3 for all three use-case



Fig. 23- PCB for Prototype 1

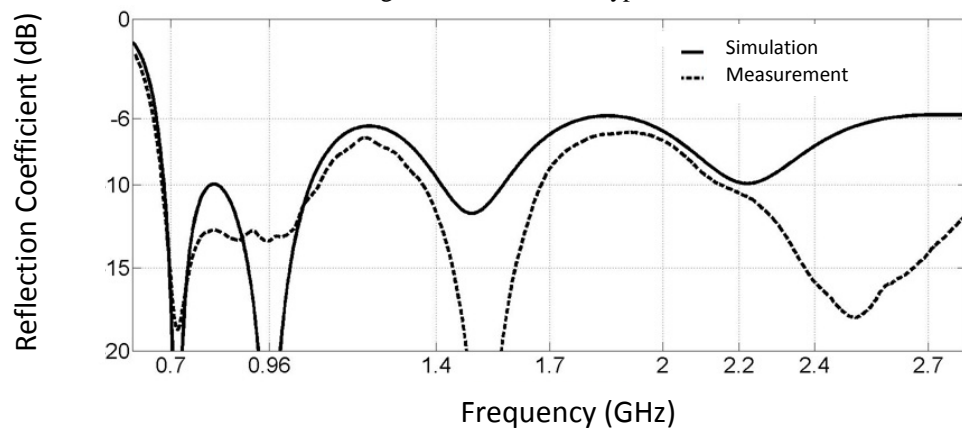


Fig. 24- Simulated and measured reflection coefficient of Prototype 1 with SAM head

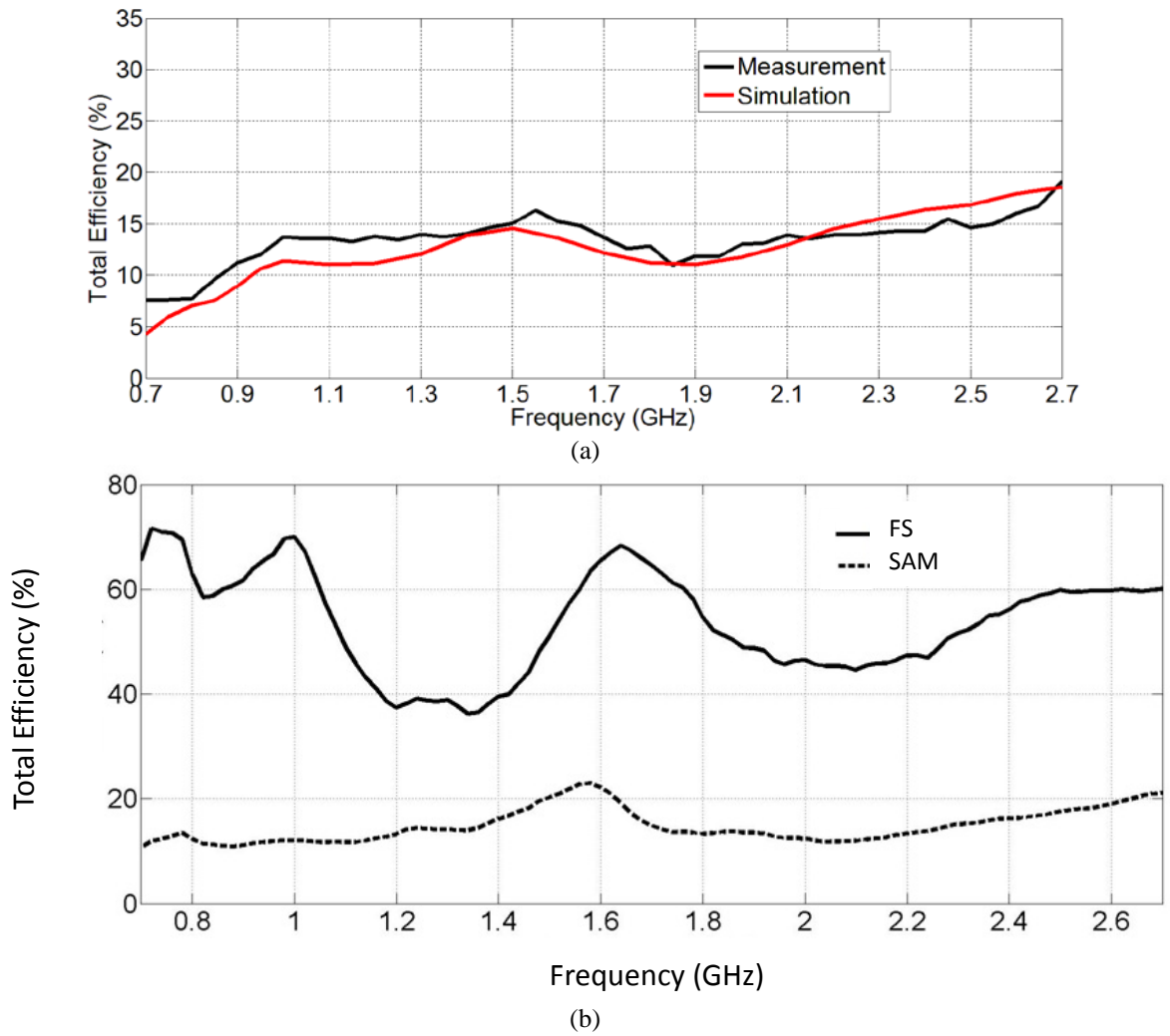


Fig. 25- (a) Comparison of simulated and measured efficiency with SAM head (b) Measured efficiency for Prototype 1 in free space (FS) and with SAM head (SAM)

For prototype 1, we achieved several reflection coefficient measurements when the eyewear was placed on real human users (Fig. 26). Two of those measurements are shown in Fig. 27 (two different users): they are very similar and stay below -6dB from 700 to 2700 MHz. The agreement with the simulated reflection coefficient of the eyewear placed over the SAM head is fair but not fully compliant.

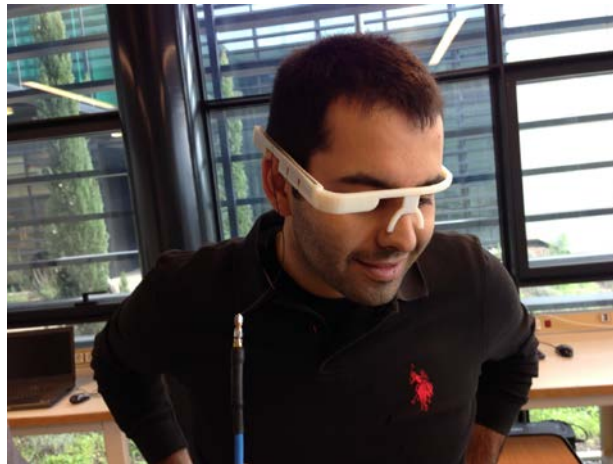


Fig. 26- Measured reflection coefficient of prototype 1 with real user

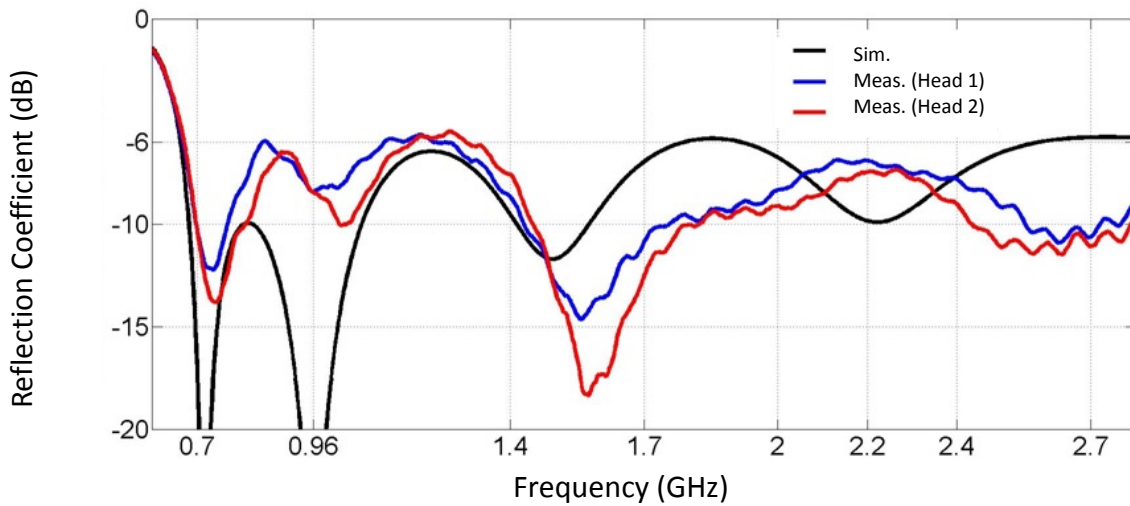


Fig. 27- Measured reflection coefficient of prototype 1 for two different real users.
Simulated curve is obtained with eyewear place over the SAM head.

In Fig. 28, we show two reflection coefficient measurements obtained with a short and a long WFL cable (calibration is done until the end of those cables therefore taking into account their losses). The two measurement results are generally in agreement, although some ripples are seen for the measurement with long cable.

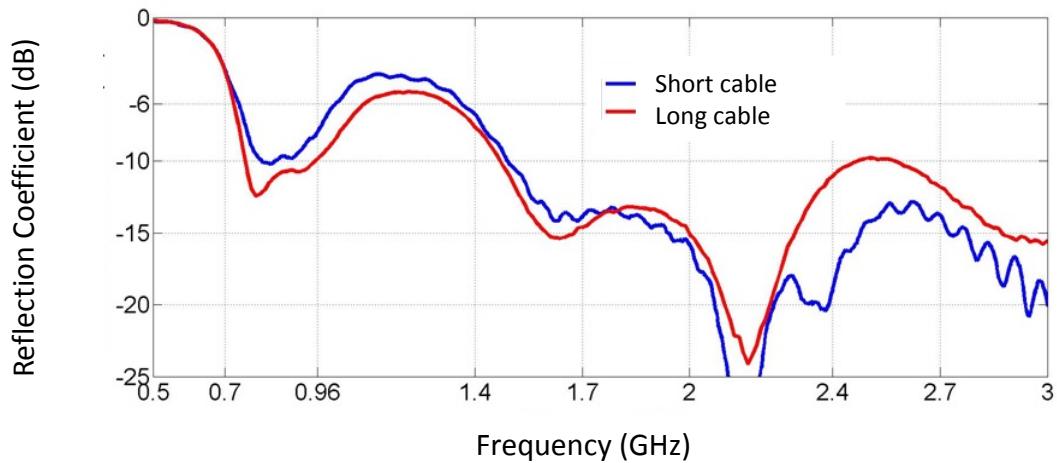


Fig. 28- Measured reflection coefficient of Prototype 1 with short and long WFL cable

SAR simulations have been also done with those new prototypes. Similar behaviors as the ones found in the feasibility study have been found: 1g SAR values are higher than the limit and 10g SAR values are lower than the limit. The cut-plane where the SAR values are extracted is presented in Figure 29a and one of the results obtained at 700 MHz is shown in Fig. 29b (not normalized). A strong distribution of the E-field is found close to the eye of the user.

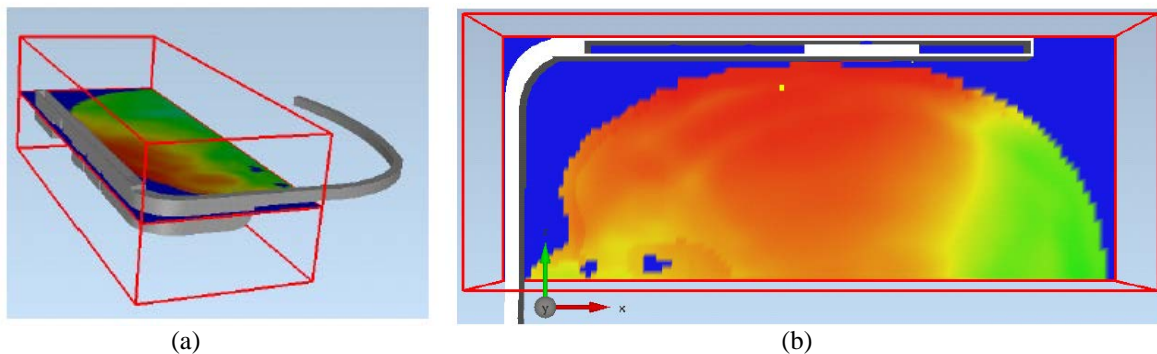


Fig. 29- 1g SAR simulated distribution in VH head at 700 MHz for one of the prototype

3 Conclusion

In this paper, we presented a feasibility study to design 4G antennas (700-960MHz and 1.7-2.7GHz) for eyewear devices. Those eyewears can be connected to last generation cellular networks, Wireless Local Area Networks or wireless hotspots. Three coupling element type antennas supplied by a matching network have been evaluated in terms of reflection coefficient and total radiation efficiency when the eyewear is placed on the user's head. We also presented SAR simulations when the eyewear is positioned over an homogeneous SAM phantom and over an heterogeneous VH phantom: the SAR levels were compared to international limit values. In a second step, we presented experimental results obtained with 3D printed eyewears and coupling elements etched on classical PCB substrate where the matching circuits are optimized close to the feeding point of the coupling element. Simulated and measured values are in very good agreement: 7 to 16% and 9 to 35% total efficiency are respectively obtained for the low and high frequency bands. However, simulated SAR values are somewhat higher than authorized limits with preoccupant high electromagnetic field distribution close to the eye of the user. From our best knowledge, this is the first time such a work is performed on wireless eyewears. However, in the future, SAR reduction techniques should be studied to be compliant with the international limits. We also plan to start additional studies about eyewear with metallic frames and also the possibility to achieve MIMO (Multiple-Input-Multiple-Output) communications when integrating a second PCB and associated coupling element in the other branch of the frame.

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