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# New Wideband Compact Wearable Slot Antennas for Medical and Sport Sensors

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## Abstract

Communication, Biomedical and sports industry is in continuous growth in the last decade. Wide band compact wearable active and tunable sensors and antennas are crucial in development of new wearable Body Area Network, BAN, systems. BAN antennas should be flexible, light weight, compact and have low production cost. Slot antennas are compact and have low production costs. Slot antennas may be employed in wearable communication systems. The dynamic range and the efficiency of communication systems may be improved by using efficient wearable slot antennas. Small printed antennas suffer from low efficiency. Amplifiers may be connected to the wearable antenna feed line to increase the system dynamic range. Novel wideband passive and active efficient wearable antennas for BAN applications are presented in this paper. Active wearable antennas may be used in receiving or transmitting communication and medical systems. The slot antenna bandwidth is from 45% to 100% with VSWR better than 3:1. The slot antenna gain is around 3 dBi with efficiency from 85% to 92%. The antenna electrical parameters were computed in vicinity of the human body. The active slot antenna gain is 18 ± 2.5 dB for frequencies ranging from 200 MHz to 750 MHz. The active slot antenna gain is 12 ± 2 dB for frequencies ranging from 1.3 GHz to 3.3 GHz. The active slot antenna Noise Figure is 0.5 ± 0.3 dB for frequencies ranging from 200 MHz to 3.3 GHz. A voltage controlled diode, varactor, may be used to control the antenna electrical performance at different environments. For example an antenna located on the patient stomach has VSWR better than 2:1 at 434 MHz. However, if the antenna will be placed on the patient back it may resonate at 420 MHz. By varying the varactor bias voltage, the antenna resonant frequency may be shifted from 420 MHz to 434 MHz. The antennas presented in this paper are low cost wideband active antennas for receiving and transmitting communication systems.

**Keywords**

Wearable Sensors, Medical Applications, Active Systems, Medical and Sport Sensors

## 1. Introduction

Printed wearable antennas are widely presented in the literature in the last decade as referred in [1]-[21]. Printed slot antennas are attractive choice for wearable communication sensors and systems. Printed slot antennas features are low volume, flexibility, light weight and low production cost. Moreover, for active slot antennas the benefit of a compact low cost feed network is achieved by integrating the active components with the radiating elements on the same substrate. Novel ultra-wideband passive and active efficient wearable antennas for BAN applications are presented in this paper. The effect of human body on the electrical performance of wearable radiating sensors at microwave frequencies is not always presented in the literature. Electrical properties of human tissues have been investigated in several papers such as [22] [23]. Several wearable antennas were presented in papers in the last decade [24]-[32]. A review of wearable antennas for various applications at different frequency bands are presented in [24]. Printed antennas resonant frequency is altered due to environment condition, different antenna locations and different system mode of operation. These disadvantages may be solved by using low profile compact active and tunable antennas. Wearable printed active and tunable antennas are rarely presented in the literature. A new class of wideband active and tunable wearable antennas for medical applications is presented in this paper. Amplifiers may be connected to the wearable antenna feed line to increase the system dynamic range. Small light weight batteries supply the bias voltage to the active components. The active slot antenna computed and measured gain is around 18 dB and the active antenna Noise Figure is 0.3 dB at 450 MHz.

## 2. Wide Band Wearable Slot Antennas

A wide band wearable printed slot antenna is shown in **Figure 1**. All the antennas considered in this paper are printed on RT-DUROID 5880 dielectric substrate with dielectric constant 2.2 and 1.2 mm thick. The dimensions of all the presented slot antennas are 116 × 70 × 1.2 mm. The size of the slot antennas is reduced to 7 × 7 cm by optimizing the matching network size. The slot antennas electrical parameters are calculated and optimized by using full wave analysis momentum software [33]. The slot antenna center frequency is 2.5 GHz. The calculated S11 parameters are presented in **Figure 2**. The computed and measured antenna bandwidth is around 50% for VSWR better than 2:1. The measured antenna bandwidth is around 70% for VSWR better than 3:1. Radiation pattern of the slot antenna is shown in **Figure 3**. The antenna beam-width is around 90˚ at

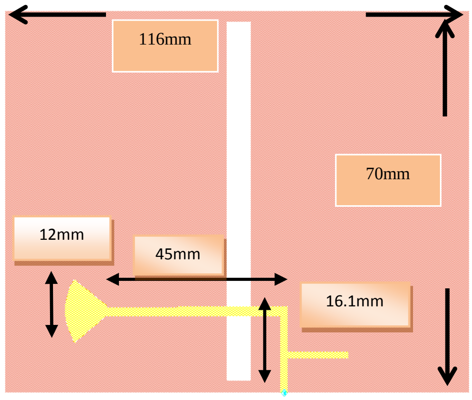


Figure 1. A wide band wearable printed slot antenna.

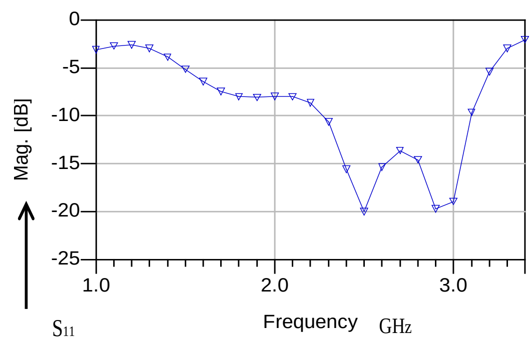


Figure 2. S11 of a wide band wearable printed slot antenna.

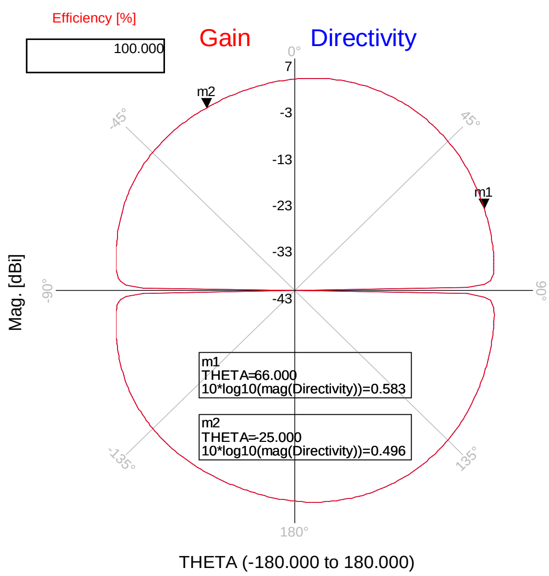


Figure 3. Radiation pattern of a wide-band wearable printed slot antenna at 2 GHz.

2 GHz, as shown in Figure 3. The computed and measured antenna gain is around 3 dBi.

## 3. Wide Band T Shape Wearable Slot Antennas

A wide band T shape wearable slot antenna is shown in Figure 4. The antenna was designed and the antenna electrical parameters were computed by using momentum software. The volume of the T shape slot antenna shown in Figure 4 is 11.6 × 7 × 0.12 cm. The slot antenna center frequency is around 2.25 GHz. The computed S11 parameters are presented in Figure 5. The antenna dimensions and the antenna matching network were optimized to achieve the antenna wider bandwidth. The antenna bandwidth is around 57% for VSWR better than 2:1. The antenna bandwidth is around 90% for VSWR better than 3:1. The antenna beam-width is around 82˚ at 1.5 GHz. The antenna gain is around 3 dBi. The computed S11 parameters of the T shape slot on human body are presented in Figure 6. The dielectric constant of human body tissue was taken as 45. The antenna was attached to a shirt with dielectric constant of 2.2 and 1 mm thick. The computed and measured antenna bandwidth is around 50% for VSWR better than 2:1. The computed and measured antenna bandwidth is around 57% for VSWR better than 3:1. The antenna center frequency is shifted by 10%. The feed network of the antenna shown in Figure 7 was optimized to match the antenna to the human body environment. The computed S11 parameters of the modified T shape slot on human body are presented in Figure 8. The modified antenna VSWR is better than 3:1 for frequencies ranging from 0.8 GHz to 3.9 GHz. The computed and measured modified slot antenna gain at 1.5 GHz is around 3 dBi. The volume of all slot antennas presented in this paper may be reduced to 7 × 7 × 0.12 cm by optimizing the feed network configuration.

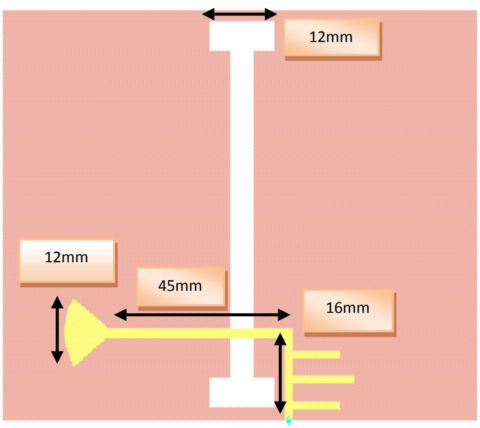


Figure 4. A wide band T shape wearable printed slot antenna.

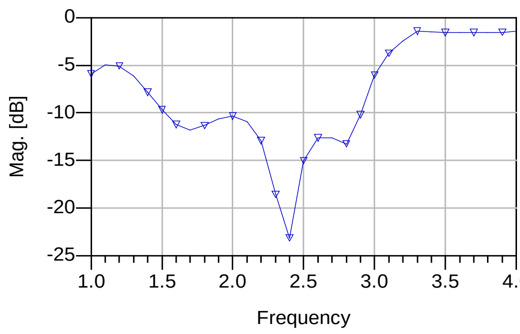


Figure 5. 10: S11 of a wide band wearable printed slot antenna.

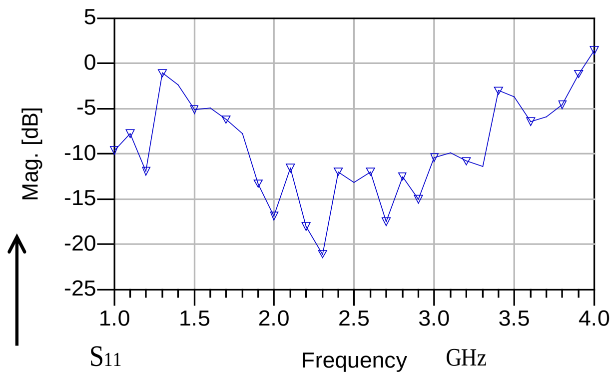


**Figure 6.** S11 of a wide band wearable printed slot antenna on human body.

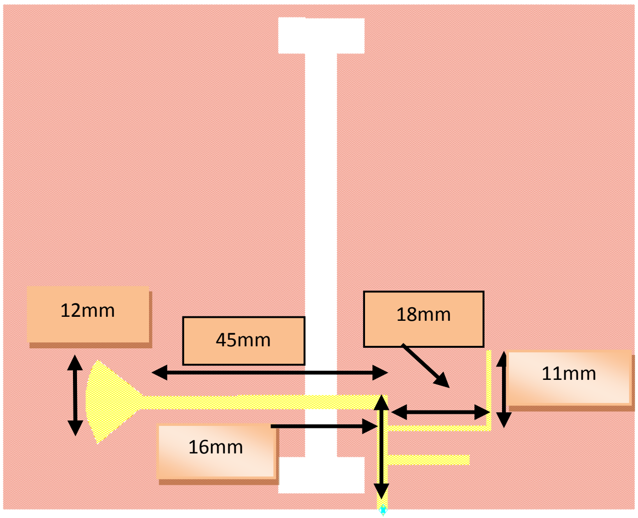


**Figure 7.** A modified wide band T shape wearable printed slot antenna.

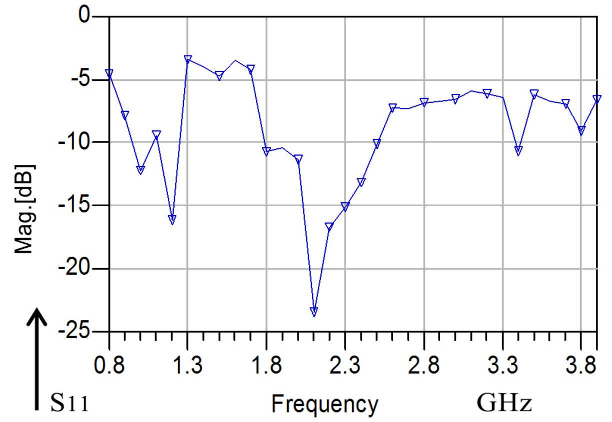


**Figure 8.** S11 of the modified T shape wearable slot antenna on human body.

## 4. Wide Band Wearable Active Slot Antennas

Active antennas (AAs) are devices combining radiating elements with active components. The radiating element is designed to provide the optimal load to the active elements. The integration of the antenna and the active components drastically reduce the complexity of the matching network. The current major applications of Active antennas are large electronically scanned arrays, phased arrays. A wide band active wearable receiving slot antenna is shown in Figure 9. Active slot antennas are devices combining radiating elements with active components such as amplifiers and diodes. The radiating element is designed to provide the optimal load to the active elements. The antenna electrical parameters was calculated and optimized by using ADS Momentum software [33]. An E PHEMT LNA, Low Noise Amplifier, was connected to a slot antenna. The radiating element is connected to the LNA via an input matching network. An output matching network connects the amplifier port to the receiver. A DC bias network supplies the required voltages to the amplifiers. The amplifier specification is listed in Table 1. The amplifier measured complex S parameters is listed in Table 2. The amplifier noise parameters are listed in Table 3. Active slot antenna S11 parameter is presented in Figure 10. The antenna bandwidth is around 40% for VSWR better than 3:1. The active slot antenna S21 parameter, gain, is presented in Figure 11. The computed and measured active antenna gain is 18 ± 2.5 dB for frequencies ranging from 200 MHz to 580 MHz. The computed and measured active antenna gain is 12 ± 2 dB for frequencies ranging from 1.3 GHz to 3.3 GHz. The active slot antenna Noise Figure is presented in Figure 12. The active slot antenna Noise Figure is 0.5 ± 0.3 dB for frequencies ranging from 200 MHz to 3.3 GHz.

Table 1. LNA amplifier specification.

| **Parameter** | **Specification** | Remarks |
|---|---|---|
| Frequency range | 0.4 - 3 GHz | |
| Gain | 26 dB @0.4 GHz<br>18 dB @2 GHz | Vds = 3 V; Ids = 60 mA |
| N.F | 0.4 dB @0.4 GHz<br>0.5 dB @2 GHz | Vds = 3 V; Ids = 60 mA |
| P1dB | 18.9 dB m @0.4 GHz<br>19.1 dB m @2 GHz | Vds = 3 V; Ids = 60 mA |
| OIP3 | 32.1 dB m @0.4 GHz<br>33.6 dB m @2 GHz | Vds = 3 V; Ids = 60 mA |
| Max. Input power | 17 dB m | |
| Vgs | 0.48 V | Vds = 3 V; Ids = 60 mA |
| Vds | 3 V | |
| Ids | 60 mA | |
| Supply voltage | ±5 V | |
| Package | Surface Mount | |
| Operating temperature | −40˚C - 80˚C | |

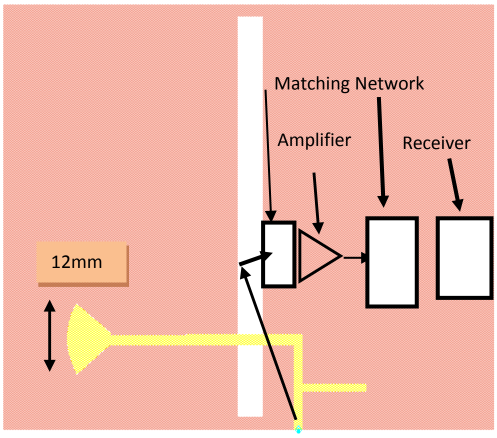


**Figure 9.** A wide band active receiving wearable slot antenna.

**Table 2.** LNA amplifier s parameters.

| F-GHz | S11 | S11˚ | S21 | S21˚ | S12 | S12˚ | S22 | S22˚ |
|---|---|---|---|---|---|---|---|---|
| 0.10 | 0.986 | −17.17 | 25.43 | 168.9 | 0.008 | 88.22 | 0.55 | −14.38 |
| 0.19 | −31.76 | 0.964 | 24.13 | 158.9 | 0.016 | 74.88 | 0.54 | −22.98 |
| 0.279 | 0.93 | −45.77 | 22.97 | 149.5 | 0.021 | 65.77 | 0.51 | −33.65 |
| 0.323 | 0.92 | −53.39 | 22.45 | 145.3 | 0.026 | 62.38 | 0.49 | −39.2 |
| 0.413 | 0.89 | −65.72 | 20.98 | 137.27 | 0.03 | 57.9 | 0.46 | −49.3 |
| 0.50 | 0.87 | −77.1 | 19.54 | 130.3 | 0.034 | 53.03 | 0.43 | −57.5 |
| 0.59 | 0.83 | −87.12 | 18.08 | 124.14 | 0.038 | 48.18 | 0.40 | −64.12 |
| 0.726 | 0.8 | −100.8 | 16.22 | 115.7 | 0.042 | 42.06 | 0.36 | −74.86 |
| 0.816 | 0.77 | −108.8 | 15.07 | 110.75 | 0.044 | 39.53 | 0.34 | −80.87 |
| 1.04 | 0.74 | −126.2 | 12.74 | 100.13 | 0.049 | 33.69 | 0.29 | −94.96 |
| 1.21 | 0.71 | −137.6 | 11.25 | 92.91 | 0.051 | 30.05 | 0.26 | −104 |
| 1.53 | 0.687 | −154.2 | 9.29 | 82.06 | 0.055 | 26.08 | 0.22 | −119 |
| 1.75 | 0.67 | −164.1 | 8.24 | 75.31 | 0.058 | 23.14 | 0.20 | −128.4 |
| 2.02 | 0.67 | −174.6 | 7.27 | 67.82 | 0.06 | 20.88 | 0.18 | −138.8 |

**Table 3.** Noise parameters.

| F-GHz | NFMIN | N11 X | N11 Y | Rn |
|---|---|---|---|---|
| 0.5 | 0.079 | 0.3284 | 24.56 | 0.056 |
| 0.7 | 0.112 | 0.334 | 36.08 | 0.05 |
| 0.9 | 0.144 | 0.3396 | 47.4 | 0.045 |
| 1 | 0.16 | 0.3424 | 52.98 | 0.042 |
| 1.9 | 0.306 | 0.3682 | 100.93 | 0.029 |
| 2 | 0.322 | 0.3711 | 106.01 | 0.029 |
| 2.4 | 0.387 | 0.3829 | 125.79 | 0.029 |
| 3 | 0.484 | 0.401 | 153.93 | 0.036 |
| 3.9 | 0.629 | 0.429 | −167.3 | 0.059 |
| 5 | 0.808 | 0.4645 | −125.53 | 0.11 |
| 5.8 | 0.937 | 0.4912 | −99.03 | 0.162 |
| 6 | 0.969 | 0.498 | −92.92 | 0.177 |

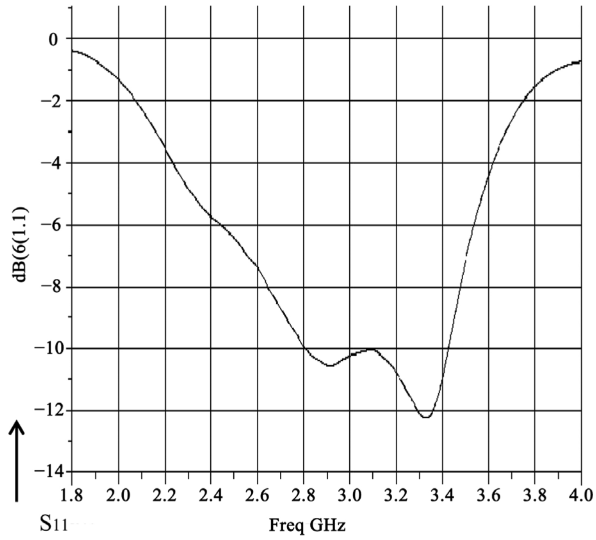


**Figure 10.** Active slot antenna S11 parameter.

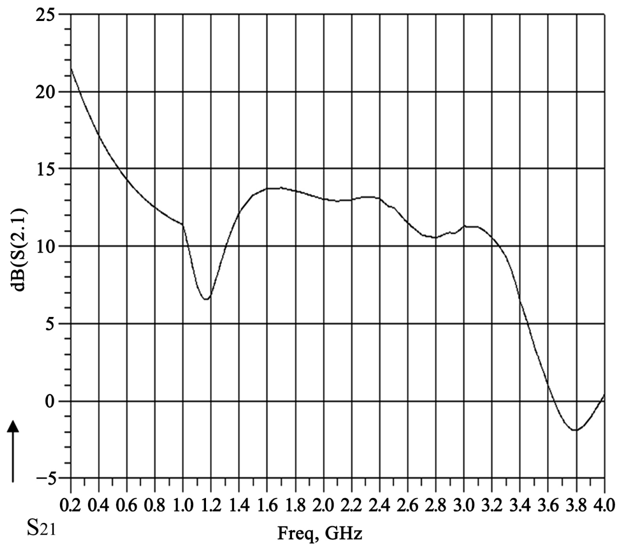


**Figure 11.** Active slot antenna S21 parameter, gain.

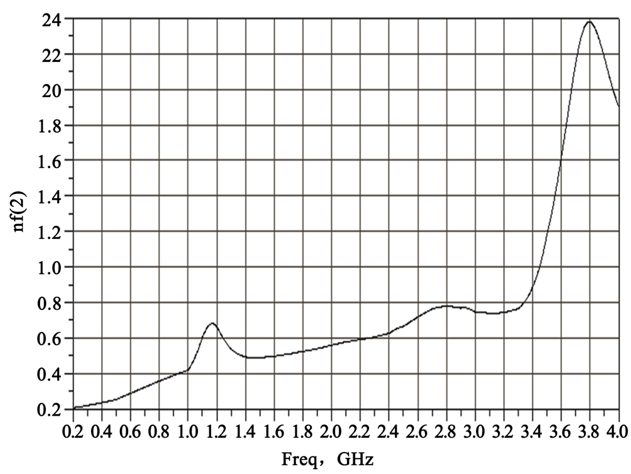


**Figure 12.** Active slot antenna noise figure.

## 5. Wearable Active T Shape Slot Antennas

A wide band active wearable receiving T shape slot antenna is shown in Figure 13. The radiating element is designed to provide the optimal load to the active elements. The antenna electrical parameters was calculated and tuned by using CAD tools. The size of the slot antenna shown in Figure 13 is 11.6 × 7 cm. The radiating element is connected to the LNA via an input matching network. An output matching network connects the amplifier port to the receiver. The antenna dimensions and the antenna matching network were optimized to achieve the antenna wider band width. A DC bias network supplies the required voltages to the amplifiers. The amplifier specification is listed in Table 1. The amplifier complex S parameters are listed in Table 2.

The amplifier noise parameters are listed in Table 3. Active slot antenna S11 parameter is presented in Figure 14. The antenna bandwidth is around 40% for VSWR better than 2:1. The active slot antenna S21 parameter, gain, is presented in Figure 15. The active computed and measured antenna gain is 18 ± 2.5 dB for frequencies ranging from 200 MHz to 580 MHz. The active antenna gain is 12.5 ± 2.5 dB for frequencies ranging from 1 GHz to 3 GHz. The active slot antenna Noise Figure is presented in Figure 16. The active slot antenna Noise Figure is 0.5 ± 0.3 dB for frequencies ranging from 300 MHz to 3.2 GHz. Active slot antenna S22 parameter is presented in Figure 17.

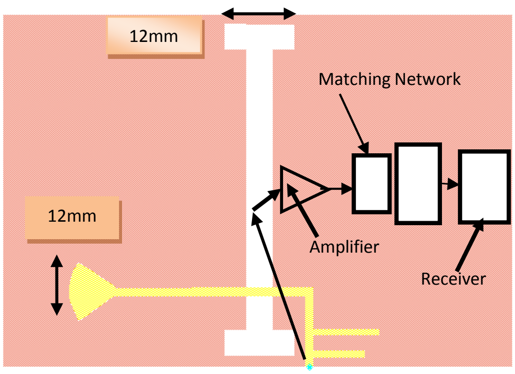


Figure 13. A wide band active receiving wearable slot antenna.

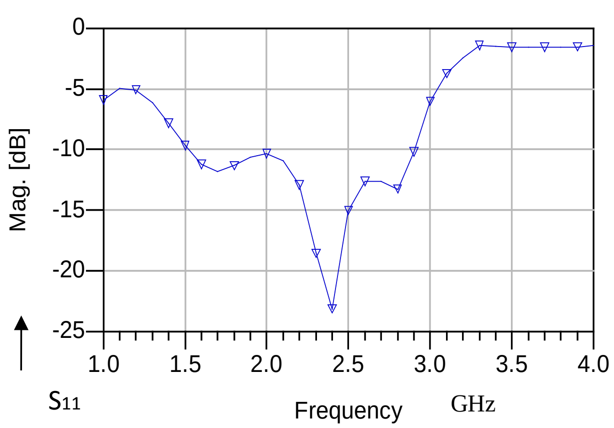


Figure 14. Active T shape slot antenna S11 parameter.

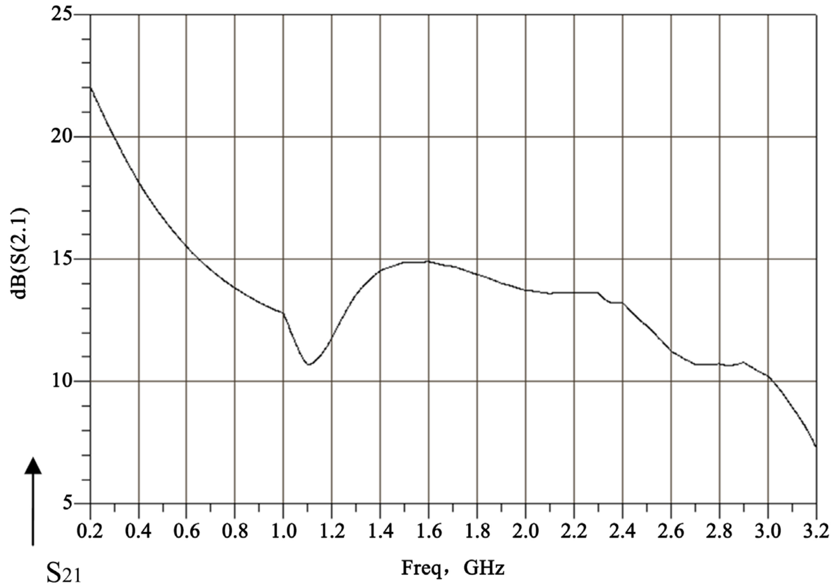


**Figure 15.** Active T shape slot antenna S21 parameter.

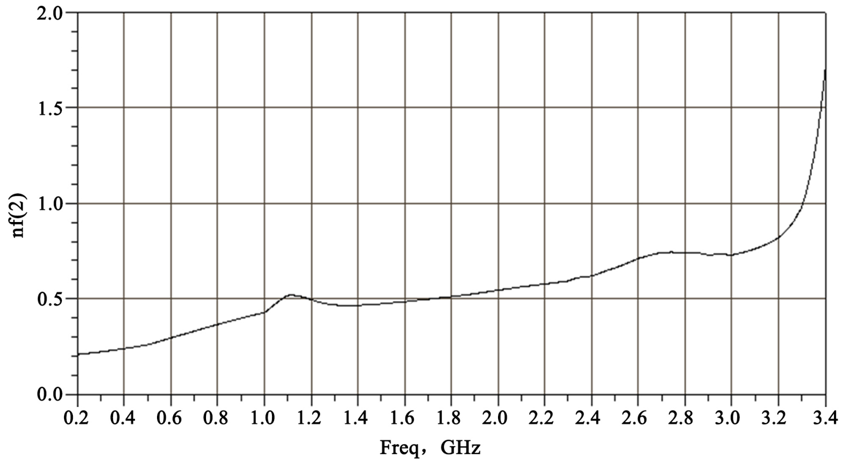


**Figure 16.** Active slot antenna noise figure.

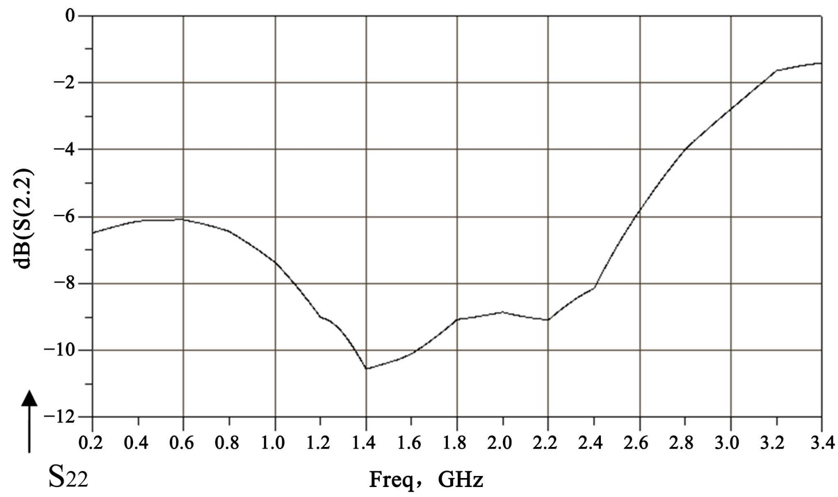


**Figure 17.** Active T shape slot antenna S22 parameter.

## 6. Wearable Tunable Slot Antennas

A wide band wearable Tunable slot antenna is shown in Figure 18. Tunable slot antennas consists of a slot antenna and of a voltage controlled diode, varactor, [1] Chapter 7. The antenna resonant frequency may be tuned by using a varactor to compensate variations in antenna resonant frequency at different locations. The antenna electrical parameters was calculated and optimized by using CAD software. The size of the tunable slot antenna shown in Figure 18 is 116 × 70 mm. A varactor is connected to the slot feed line. The varactor bias voltage may be varied automatically to set the antenna resonant frequency at different locations and environments. The varactor capacitance varies from 0.1 pF to 1 pF by varying the varactor bias voltage from 0 V to 12 V. The slot antenna center frequency is 2.5 GHz. The tunable antenna S11 parameters for varactor capacitances ranging 0.1 pF to 1 pF are presented in Figure 19. The antenna Bandwidth is around 40% for VSWR better than 2:1. The antenna bandwidth is 60% for VSWR better than 3:1.

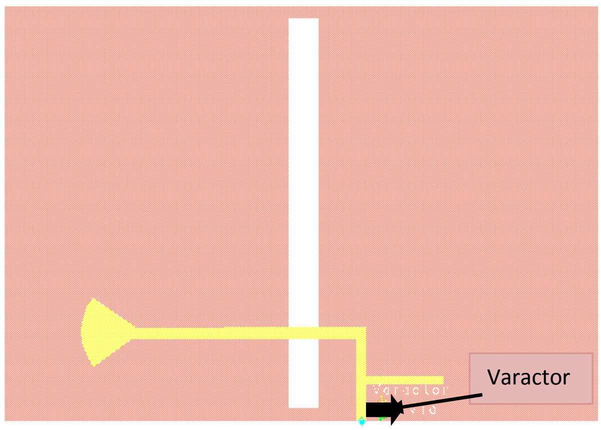


Figure 18. A wide band tunable wearable slot antenna.

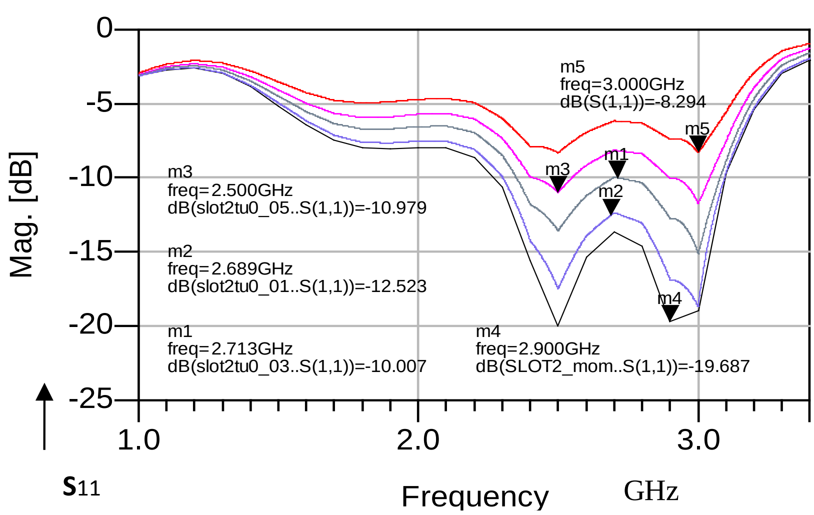


Figure 19. S11 of a wide band tunable wearable slot antenna.

## 7. Wearable Tunable T Shape Slot Antennas

A wide band T shape wearable printed slot antenna is shown in Figure 20. The antenna electrical parameters was calculated and optimized by using momentum software. The size of the T shape tunable slot antenna shown in Figure 20 is 11.6 × 7 cm. The slot antenna center frequency is around 2.25 GHz. The computed S11 parameters are presented in Figure 21. The antenna bandwidth is around 57% for VSWR better than 2:1. The antenna bandwidth is around 90% for VSWR better than 3:1. A varactor is connected to the slot feed line. The varactor bias voltage may be varied automatically to set the antenna resonant frequency at different locations and environments. The S11 parameters for varactor capacitances ranging 0.1 pF to 1 pF are presented in Figure 22.

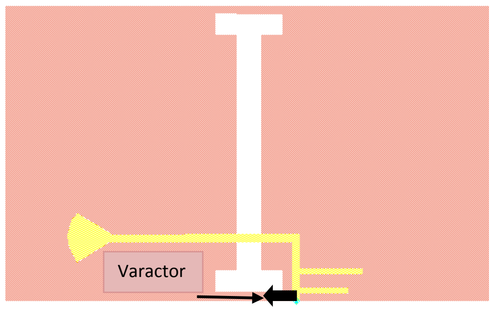


Figure 20. A wide band tunable wearable T shape slot antenna.

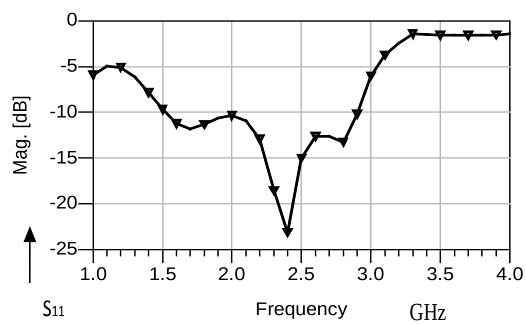


Figure 21. S11 of a wide band wearable T shape slot antenna without varactor.

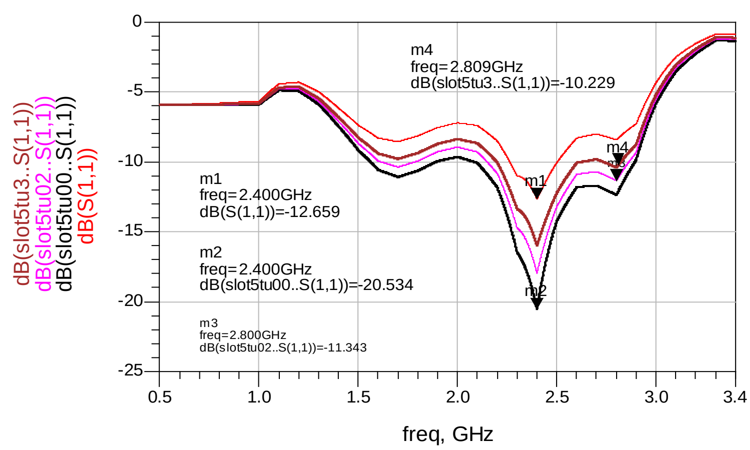


Figure 22. S11 of a wide band tunable T shape slot antenna.

## 8. Active Slot Antennas for Medical Systems

The slot antennas electrical performance in vicinity of human body was investigated by using the model presented in Figure 23. Properties of human body tissues are listed in Table 4 [23]. These properties were employed in the antenna design. Two to four active and tunable radiating sensors may be assembled in a belt and attached to the patient body as shown in Figure 24. The bias voltage to the active elements is supplied by a compact battery. The RF and DC cables from each radiator are connected to a recorder. The recorder consists of a switching matrix and low noise amplifier, filter and a signal processing unit. The receiving antennas are connected to a switching matrix. The antennas receive signals that are transmitted from various positions in the patient body. Losses due the electrical properties of human body tissues attenuate the level of the transmitted and received RF signal in vicinity of the human body. Efficient passive and active antennas improve considerably the link budget of medical communication systems. Attenuation of human body tissues in Nepers per meter are given in Table 5.

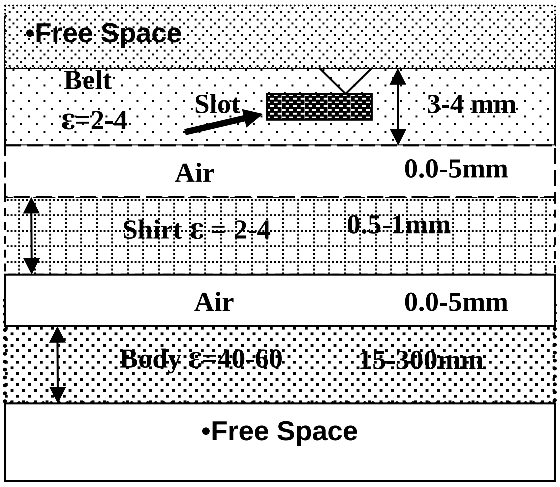


Figure 23. Analyzed structure for wearable slot antennas.

Table 4. Electrical properties of human body tissues.

| Tissue | Property | 600 MHz | 1000 MHz |
|---|---|---|---|
| Fat | $\sigma$ | 0.05 | 0.06 |
| | $\varepsilon$ | 5 | 4.52 |
| Stomach | $\sigma$ | 0.73 | 0.97 |
| | $\varepsilon$ | 41.41 | 39.06 |
| Colon | $\sigma$ | 1.06 | 1.28 |
| | $\varepsilon$ | 61.9 | 59.96 |
| Lung | $\sigma$ | 0.27 | 0.27 |
| | $\varepsilon$ | 38.4 | 38.4 |
| Prostate | $\sigma$ | 0.75 | 0.90 |
| | $\varepsilon$ | 50.53 | 47.4 |
| Kidney | $\sigma$ | 0.88 | 0.88 |
| | $\varepsilon$ | 117.43 | 117.43 |

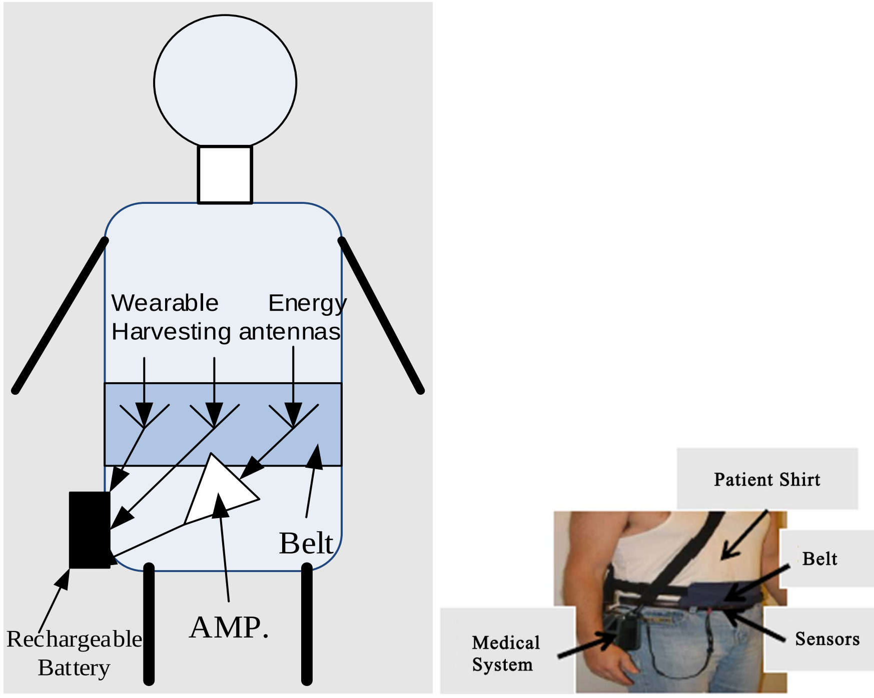


**Figure 24.** Active Wearable Sensors for medical applications.

**Table 5.** Attenuation of human body tissues.

| Tissue | Attenuation Nepers/m 500 MHz | Attenuation Nepers/m 1000 MHz |
|---|---|---|
| Fat | 3.92 | 4.66 |
| Stomach | 19.33 | 25.71 |
| Blood | 38.96 | 46.34 |
| Skin | 16.68 | 21.02 |
| Pancreas | 20.13 | 26.41 |

For example RF signal attenuation at 500 MHz in blood in Nepers per meter is 38.96. RF signal attenuation at 500 MHz for stomach tissues in Nepers per meter is 19.33. During the medical test the highest signal level is selected and transferred to the signal processing unit. For example for the slot antenna shown in Figure 1 the antenna resonant frequency in vicinity of the patient stomach is shifted by 5%. During the medical system operation the varactors bias voltage may be varied automatically to tune the medical device to the desired system frequency. Active and tunable antennas may be placed on the patient body in several locations to improve the level of the received signal from different positions in the patient body.

## 9. Conclusion

This paper presents compact Ultra-Wideband novel wearable active slot antennas in frequencies ranging from 0.5 GHz to 4 GHz. The active slot antennas were analyzed by using 3 D full-wave software. The active slot antenna bandwidth is from 45% to 100% with VSWR better than 3:1. The computed and measured slot antenna gain is around 3dBi with efficiency higher than 90%. The antenna electrical parameters were computed in vicinity of the human body. The computed and measured active slot antenna gain is 18 ± 2.5 dB for frequencies ranging from 200 MHz to 750 MHz. The computed and measured active slot antenna gain is 12 ± 3 dB for frequencies ranging from 1.1 GHz to 3.4 GHz. This paper presents also new compact Ultra-Wideband tunable wearable slot antennas in frequencies ranging from 0.5 GHz to 4 GHz. A varactor is employed to compensate variations in the antenna resonant frequency at different locations on the human body. These wideband efficient passive and active wearable antennas were not presented up to date in the literature. These novel passive and active wearable antennas may be used in receiving or transmitting channels. In transmitting channels, a power amplifier is connected to the antenna. In receiving channels, a low noise amplifier is connected to the receiving antenna. The active antenna gain flatness is limited to ±2.5 dB due to the amplifiers S parameter characteristics. In future work we can choose amplifiers with better gain flatness and with wider band width.

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