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Compact Wearable Meta Materials Antennas for Energy Harvesting Systems, Medical and IOT Systems

Albert Sabban

Department of Electrical Engineering
Kinneret and Ort Braude Colleges, Israel
sabban@netvision.net.il

Abstract- Demand for green technologies and energy is in continuous growth in the last years. Compact efficient antennas are crucial for energy harvesting portable systems. Small antennas have low efficiency. The efficiency of communication and energy harvesting systems may be improved by using efficient passive and active antennas. The system dynamic range may be improved by connecting amplifiers to the printed antenna feed line. Design, design considerations, computed and measured results of wearable meta-materials antennas with high efficiency for energy harvesting applications are presented in this paper. All antennas were analyzed by using 3D full-wave software. The antennas electrical parameters on human body are presented. The directivity and gain of the antennas with Split-ring resonators, SRR, is higher by 2.5dB than the antennas without SRR. The resonant frequency of the antennas with SRR is lower by 5% to 10% than the antennas without SRR.

Index Terms - Metamaterial antennas, Printed antennas, Energy harvesting, Medical systems

I. INTRODUCTION

Wearable medical, 5G and IOT systems cannot function without using batteries and power cords. Energy harvesting systems may eliminate the need to replace batteries every day and the usage of power cords. In order to use as much free space energy as possible it is important to collect the electromagnetic power from several wireless communication systems. Due to low-power densities, highly efficient antennas are crucial. Number of methods to produce electricity from light, heat, radio waves and vibration have been developed [1-3]. Several printed antennas were employed for harvesting energy applications [1-6]. Patch and other printed antennas are widely used in communication and medical system [7-26]. However, small printed antennas suffer from low efficiency. Meta material technology is used to design compact printed antennas with high efficiency for energy harvesting systems. Artificial media with negative dielectric permittivity were presented in [6]. Periodic SRR and metallic posts structures may be used to design materials with dielectric constant and permeability less than 1 as presented in [6]-[7]. In this paper meta-material technology is used to develop small antennas with high efficiency for energy harvesting systems. Electrical properties of human tissues have been investigated in several papers such as [15-16]. Wearable antennas have been presented in papers in the last years as referred in [1-5]. The computed and measured bandwidth of the antenna with SRR and metallic strips for energy harvesting applications is around 50% for VSWR of 2.3:1.

II. ENERGY HARVESTING SYSTEMS

There is a significant increase in the amount of electromagnetic energy in the air in the last decade. In electromagnetic energy harvesting systems radio waves propagating in free space are captured, stored and used to charge batteries and for other applications. The expected amount of radio wave in the air in 2013 was 1.5 Exa-bytes per month. However, the expected amount of radio wave in the air in 2017 was 11 Exa-bytes per month. Today we can do more computations per KWh. In 2010 we could do 15,000,0000 computations per KWh. Wireless communication systems operate in the frequencies from 700MHz to 2700MHz. Medical systems operate in the frequencies from 200MHz to 1200MHz. WLAN systems operate in the frequencies from 5.2GHz to 6GHz. We may collect electromagnetic energy from 0.2GHz up to 6GHz. Energy sources used in harvesting systems are listed in Table 1. Harvested power from indoor RF energy sources is around 0.1 $\mu W/cm^2$. Harvested power from RF energy sources in malls and stadiums may increase to around $1mW/cm^2$. RF energy is inversely proportional to distance and therefore decrease as the distance from a source is increased. The harvesting energy system operates as a Dual Mode Energy harvesting system. The Low Noise Amplifier is part of the receiving system. The LNA DC bias voltages are supplied by the receiving system DC unit.

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Table 1: Energy sources used in harvesting systems

Energy Source	Type	Efficiency	Harvested Power
Light	Free space	10~25%	100 mW/cm²
Thermal energy	Human Industrial	~0.1% ~3%	60 µW/cm² 1-10 mW/cm²
Vibration energy	~Hz–human ~kHz–machines	20~50%	~4 µW/cm³ ~800 µW/cm³
RF energy	0.9 – 2.7GHz Indoor	~50%	0.1 µW/cm²
RF energy	0.9 – 2.7GHz At malls	~50%	1mW/cm²

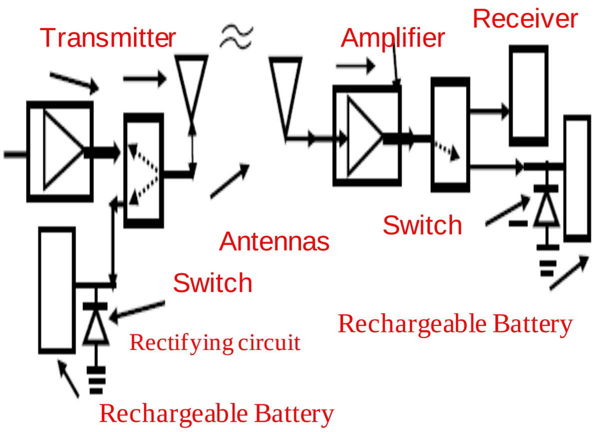

Fig.1. Dual Mode Energy harvesting concept

As presented in Fig. 1 the energy harvesting system consists of an antenna, a rectifying circuit and a rechargeable battery. A rectifier is a circuit that converts electromagnetic energy, alternating current AC, to direct current (DC). Half wave rectifier or full wave rectifier may be used to convert electromagnetic AC energy to DC electrical energy. A Half wave rectifier is presented in Fig. 2. A half-wave rectifier operates only during the positive half cycle. It allows only one half of an AC waveform to pass through the load. The rectifier output DC voltage, V_{ODC} , is given in equation 1. The rectifier output voltage may be improved by connecting a capacitor in shunt to the resistor as presented in Fig. 3.

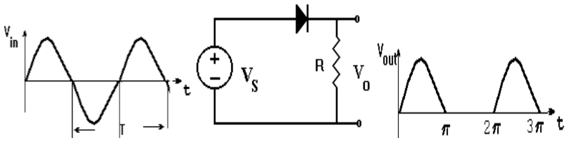

Fig. 2: Diode Half wave rectifier

$$V_{O,DC} = \frac{1}{2\pi}\int_{0}^{2\pi} V_O^{MAX}\sin(\omega t)d(\omega t); \quad \omega = 2\pi f$$

$$V_O = V_S - V_{DON} \approx V_S; \quad V_O{}^{MAX} = V_m \qquad (1)$$

$$V_{ODC} = V_m / \pi$$

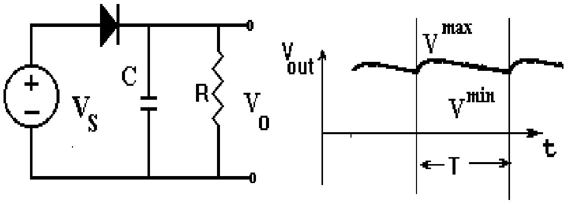

Fig. 3: Improved half wave diode rectifier

$$Vripple = Vr = Vmax - Vmin = {VDC}/{fCR} \quad (2)$$

The time constant τ should be lower than T. Where, $\tau = RC \ll T$. The half wave rectifier efficiency is 40.6%, see equation 3.

$$\eta = \frac{\text{DC output power}}{\text{AC input power}} = \frac{\left(\frac{Im}{\pi}\right)^2 R}{\left(\frac{Im}{2}\right)^2 (R+rf)} \sim 0.406 \quad (3)$$

The diode bridge full wave rectifier circuit is used for DC power supplies. It consists of four diodes D1 through D4, as shown in in Fig. 4, connected to form a bridge. During the positive input half cycle, terminal A will be positive and terminal B will be negative. Diodes D1 and D2 will become forward biased and D3 and D4 will be reversed biased. The rectifier output DC voltage, $V_{ODC} = 2V_m / \pi$, The rectifier output voltage may be improved by connecting a capacitor in shunt to the resistor. The improved half wave rectifier is presented in Fig. 5. The half wave rectifier efficiency is 81.2% as presented in equation 4.

$$\eta = \frac{\text{DC output power}}{\text{AC input power}} = \frac{\left(\frac{2Im}{\pi}\right)^2 R}{\left(\frac{Im}{2}\right)^2 (R+rf)} \sim 0.812 \quad (4)$$

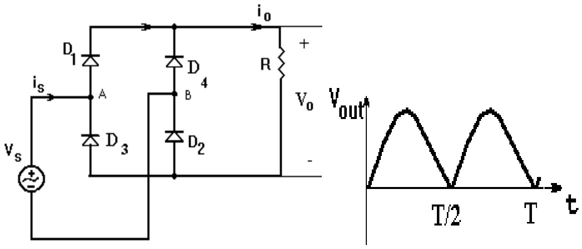

Fig. 5: Full wave bridge diode rectifier

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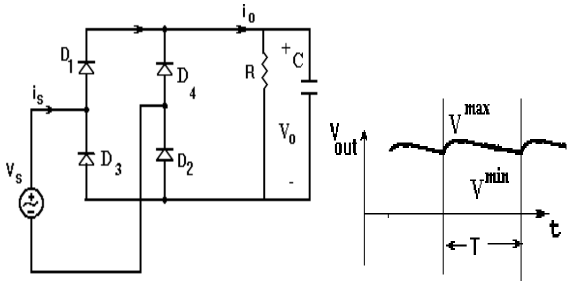


Fig. 6: Full wave bridge diode rectifier

A capacitor is used to improve the flatness of the rectifier output voltage variation as function of time as shown in Fig. 6. The capacitor may be a voltage-controlled varactor diode. Varactors are voltage variable capacitors used to provide electronic tuning to electrical devices. The output voltage ripple, see equation 3, of the rectifier may be tuned as function of frequency of the received signal or of the load resistance R. A Schottky diode may be used in the rectifier circuit. Schottky diodes are semiconductor diodes which has a low forward voltage drop and a very fast switching action. There is a small voltage drop across the diode terminals when current flows through the diode. The voltage drop of a Schottky diode is usually between 0.2V to 0.4 volts. This lower voltage drop provides higher switching speed and better system efficiency. Fig. 7. Presents a wearable harvesting system and a wearable battery charger attached to the patient shirt.

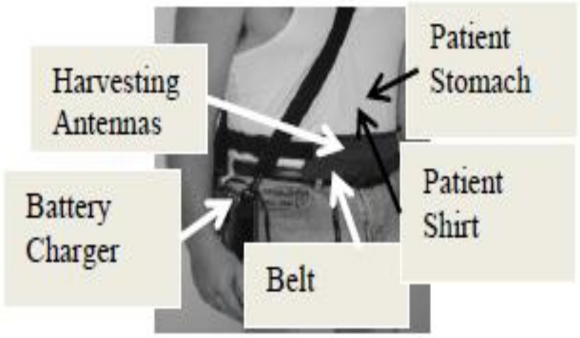


Fig. 7: Medical Wearable Harvesting System

III. WEARABLE ANTENNA WITH SRR and METALLIC STRIPS

A printed antenna with SRR and metallic strips is shown in Fig. 8. The microstrip loaded dipole antenna with SRR in Fig. 8 provides horizontal polarization. The slot antenna provides vertical polarization. The resonant frequency of the antenna with SRR is around 330MHz. The resonant frequency of the antenna without SRR is 10% higher. The antennas shown in Fig. 8 consist of two layers. The dipole feed network and metallic strips is printed on the first layer. The radiating dipole with SRR is printed on the second layer. The thickness of each layer is 0.8mm. The dipole and the slot antenna create dual polarized antenna. The computed S11 and antenna gain are presented in Fig. 9. The length of the antenna shown in Fig. 1 is 19.8cm. The antenna bandwidth is around 40% for VSWR better than 2.5:1. The 3D computed radiation pattern is shown in Fig. 10. Directivity and gain of the antenna with SRR are around 5.5dBi as shown in Fig. 11. The feed network of the antenna in Fig. 8 was optimized to yield VSWR better than 2:1 in frequency range of 250MHz to 420MHz as shown in Fig. 12. The SRR have an important role in the radiation characteristics of the antenna. The antenna with SRR and metallic strips was optimized to yield wider bandwidth as shown in Fig. 13. The S_{11} parameter of the modified antenna with metallic strips is presented in Fig. 14. The antenna bandwidth is around 50% for VSWR better than 2.3:1.

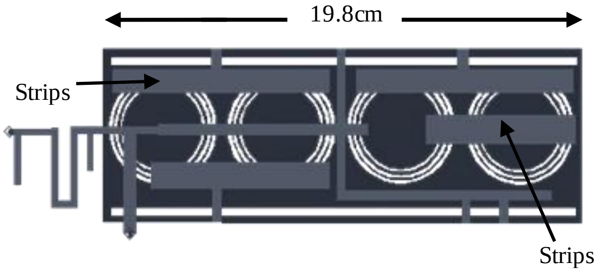


Fig. 8. Antenna with SRR and Metallic strips

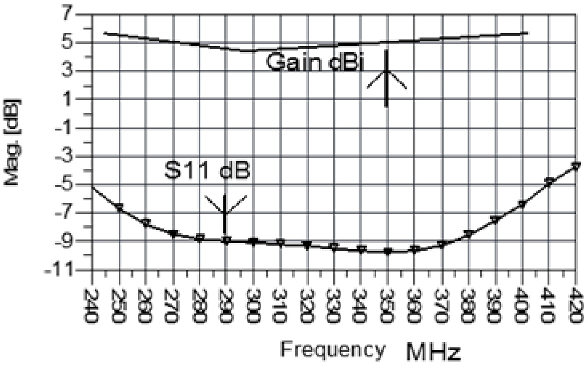


Fig. 9. S11 for antenna with SRR and metallic strips

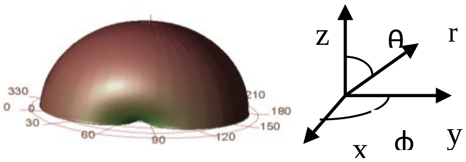


Fig. 10. 3D Radiation pattern for antenna with SRR and metallic strips

Comparison between Antennas with and without SRR is given in Table 2. The measured results agree with the computed results.

Table 2: Comparison between Antennas with SRR

Antenna	Freq. (MHz)	VSWR %	Gain (dBi)	Length (cm)
With SRR	350	10	5.5	19.8
Without SRR	400	10	2.5	21
SRR and Strips	300	50	5.5	19.8

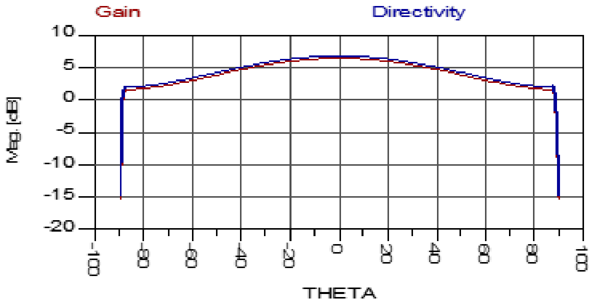


Fig. 11. Directivity of the antenna with SRR

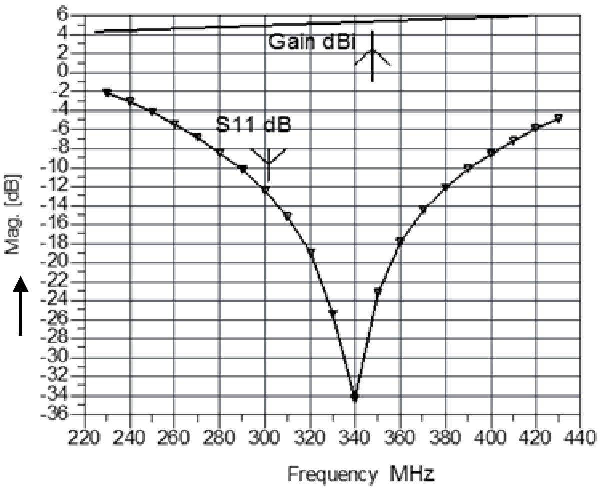


Fig. 12. S11 and gain for antenna with metallic strips

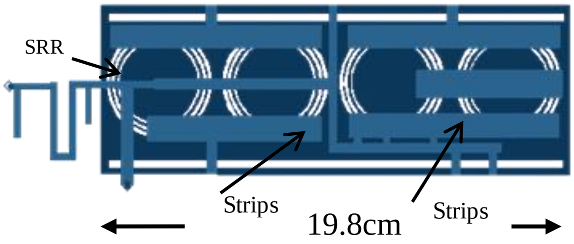


Fig. 13. Wideband antenna with SRR and Metallic Strips

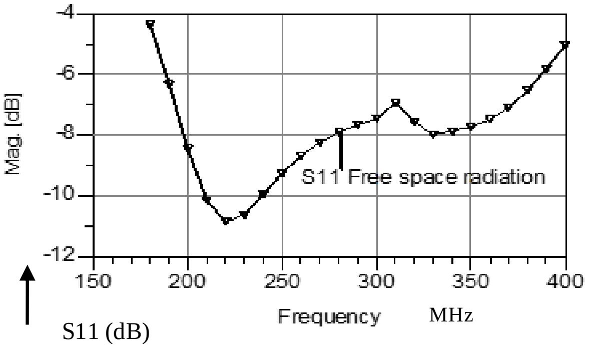


Fig. 14. S11 for antenna with SRR and metallic strips

IV. METAMATERIAL ANTENNAS IN VICINITY TO THE HUMAN BODY

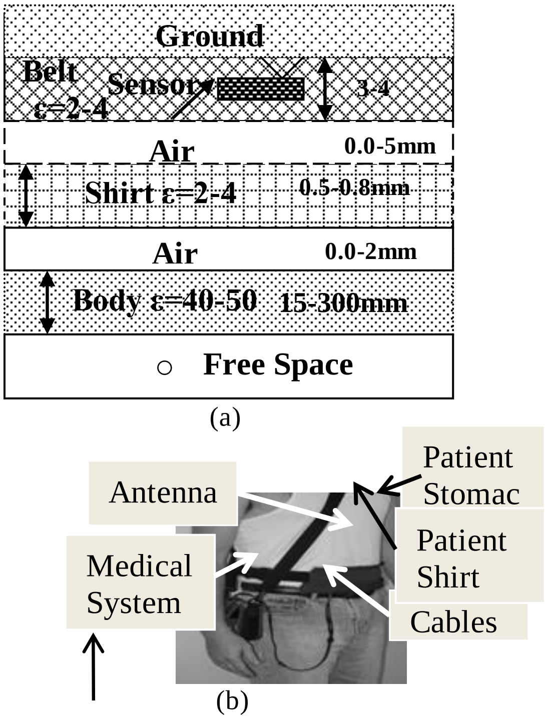
The meta-materials antennas S11 variation near the human body were computed by using the structure presented in Fig. 15a. Electrical properties of human body tissues are given in Table 3 see [15]. The antenna location on the human body is taken into account by computing S11 for different dielectric constant of the body tissues. The variation of the dielectric constant of the body from 43 at the stomach to 63 at the colon zone shifts the antenna resonant frequency by to 2%. The antenna was placed inside a belt with thickness between1 to 4mm as shown in Fig. 15b. The belt dielectric constant was varied from 2 to 4. The antennas impedance was computed and measured for air spacing of 0mm to 8mm, between the patient shirt and the antennas. The dielectric constant of the patient shirt was varied from 2 to 4. Fig. 16 presents S11 results of the antenna with SRR and metallic strips. The antenna resonant frequency is shifted by 1%. Results presented in Fig. 16 indicate that the antenna has V.S.W.R better than 2.3:1 for 50% bandwidth. The radiation pattern of the antenna with SRR and metallic strips on human body is presented in Fig. 17. Fig. 18 presents S11 results for different belt thickness, shirt thickness and air spacing between the antennas and Human body for the antenna without SRR. One may conclude from results shown in Fig. 18 that the antenna has S11 better than -9.5dB for air spacing up to 8mm between the antennas and the human body.

Table 3: Electrical properties of body tissues

Tissue	Property	434 MHz	600 MHz	1000 MHz
Fat	σ ε	0.045 5.02	0.05 5	0.06 4.52
Stomach	σ ε	0.67 42.9	0.73 41.41	0.97 39.06
Colon	σ ε	0.98 63.6	1.06 61.9	1.28 59.96
Lung	σ ε	0.27 38.4	0.27 38.4	0.27 38.4
Kidney	σ ε	0.88 117.43	0.88 117.43	0.88 117.43

V. WEARABLE HARVESTING SYSTEM

The proposed meta-materials antennas may be placed on the patient body as shown in Fig. 19a. The patient in Figures 19a and 19b presents



(a)

(b)

Fig. 15. a. Antenna environment b. Patient

Patients wearing a wearable antenna. The antennas belt is attached to the patient front or back body. The cable from each antenna is connected to the medical system. The received signals are combined by a power combiner and transferred via a switch to the receiver and to the harvesting system as presented in Fig. 20. In several wearable systems the distance separating the transmitting and receiving antennas is in the near field zone. In the near-field area the antennas are magnetically coupled and only near field effects should be considered. The antennas electrical characteristics on human body may be measured by using a phantom that represents the human body electrical properties as presented in [5].

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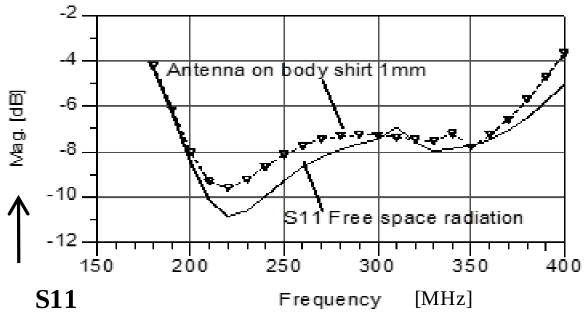

Fig. 16. Antenna with SRR S11 results on a patient

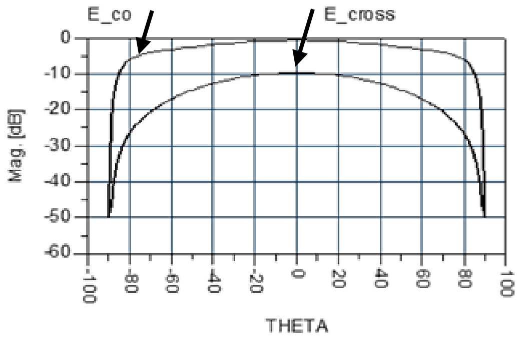

Fig. 17. Radiation pattern for antenna with SRR shown in Fig. 13 on the Human body

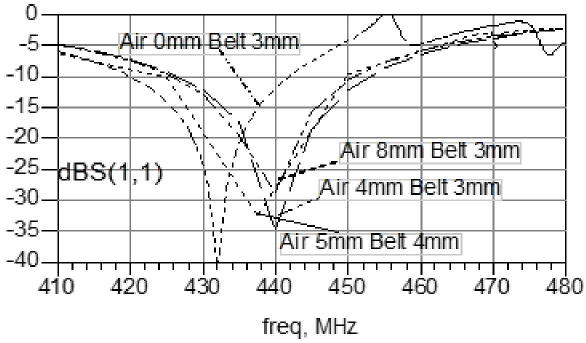

Fig. 18. S11 results for different locations relative to the Patient body for the antenna without SRR

Usually the received signal during medical test with thin persons is lower than the received signal during medical test with fat persons. The explanation is that the dielectric constant and

S11

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conductivity of muscle is much higher than the dielectric constant and conductivity of fat tissues. Properties of human body tissues should be considered in the design of wearable antennas.

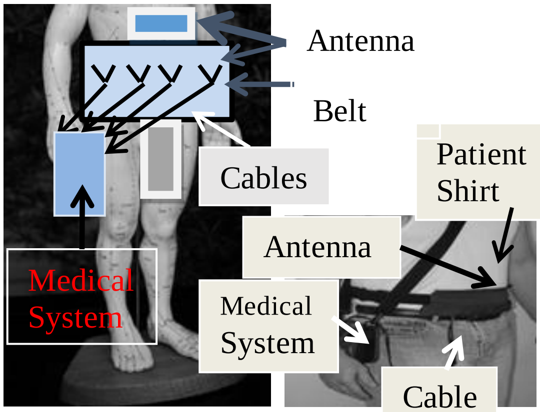

Fig. 19. a. Medical system with Wearable antennas b. Patient with printed Wearable antenna

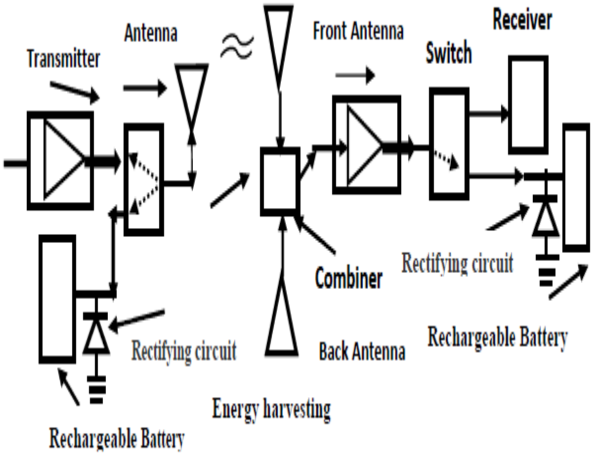

Fig. 20. Wearable Harvesting System

VI. ACTIVE METAMATERIAL RECEIVING WEARABLE ANTENNA

Figure 20 presents a basic receiver block diagram. Receiving active antenna layout is shown in Fig. 21. A matching network match the antenna with SRR to the LNA. The LNA, TQP3M9028 Tri-Quint LNA, is a high linearity gain block amplifier. At 1.9 GHz, the amplifier typically provides 14dB gain, output P1dB 20dBm and 1.8 dB Noise Figure. An output matching network match the amplifier to the receiver. A DC bias network supply the required voltages to the amplifiers. The active receiving metamaterial antenna gain is 11±2dB from 150MHz to 900MHz as shown in Fig. 22.

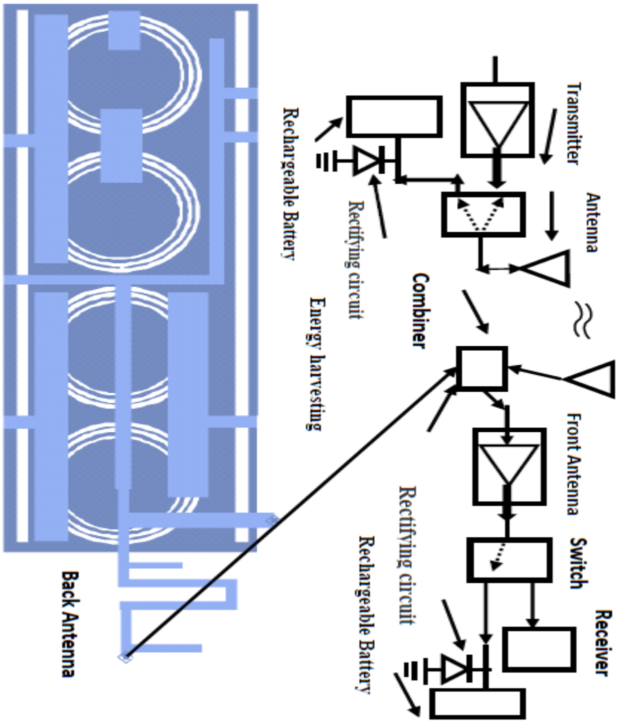

Fig. 21. Wearable dual mode harvesting system

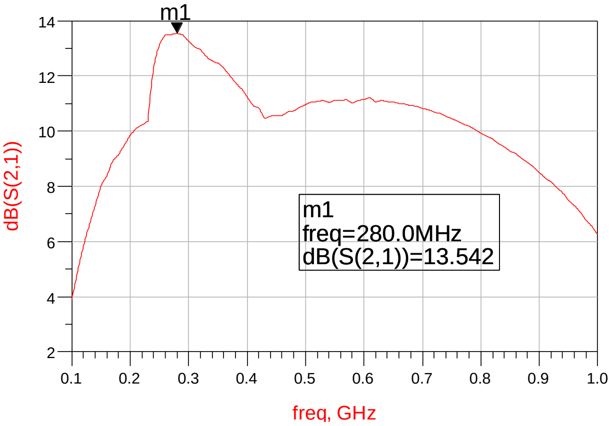

Figure 22: Active receiving antenna gain

A photo of the feed network and metallic strips is shown in Fig. 23a. A photo of antenna with SRR is shown in Fig. 23b. Comparison of electrical parameters of compact wearable antennas for medical, 5G and IOT systems is listed in Table 4.

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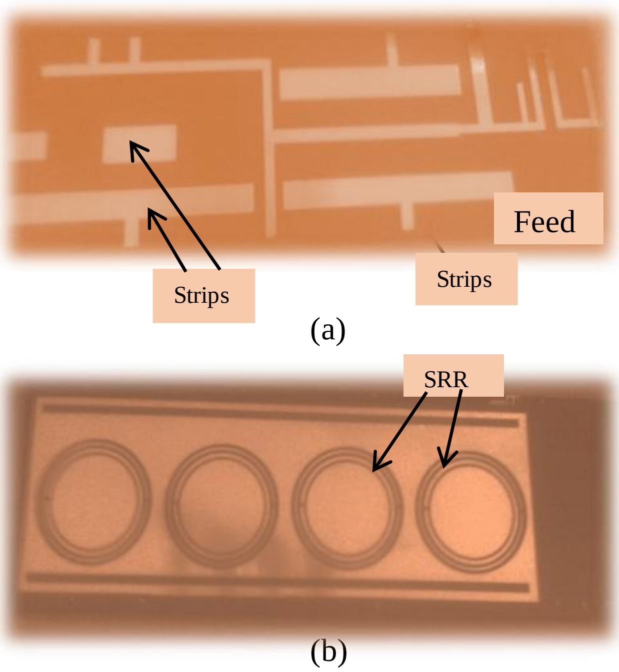

(a)

(b)

Fig. 23: Photo of antenna with SRR and Metallic strips a. feed network and metallic strips b. Antenna with SRR

Table 4: Comparison of electrical characteristics of wearable antennas

Antenna	**Bandwidth %**	VSWR	Gain dBi
Printed dipole	5-10	2:1	2-3
Dipole with SRR	8-12	2:1	5-7
SRR and strips	50	2.5:1	5-7.5
Loop	5-10	4:1	0
Patch	1-3	2:1	2-3
Stacked Patch	10-15	2:1	4-5
Slot	50	2:1	3
T shape slot	60	2:1	3
Active slot	40	3:1	12-20
Active T slot	50	3:1	12-20
Active with SRR	50	2.5:1	10-16

VII. CONCLUSION

Meta material technology is used to develop small antennas with high efficiency for medical and IOT systems. This paper presents new Ultra-Wideband wearable passive and active energy harvesting systems and antennas in frequencies ranging from 0.4GHz to 8GHz. The antennas are inserted in a belt and attached to the body. The antennas are compact and can be attached to the body. The antennas allow the patients easy movement (running, jumping and working).

The electromagnetic energy is converted to DC energy that may be employed to charge batteries, wearable medical devices and commercial Body Area Networks, BANs. A new class of wideband printed meta-materials antennas with high efficiency is presented. The bandwidth of the antenna with SRR and metallic strips is around 50% for VSWR better than 2.3:1. Optimization of the feed network, number of the coupling stubs and the length of the coupling stubs may be used to tune the antenna resonant frequency, radiation characteristics and the number of resonant frequencies. The length of the antennas with SRR is smaller by 10% than the antennas without SRR. Moreover, the resonant frequency of the antennas with SRR is lower by 5% to 10% than the antennas without SRR. The gain and directivity of the patch antenna with SRR is higher by 2 to 3dB than the patch antenna without SRR. Measured results agree with computed results.

Harvested power from RF transmitting links is usually lower than 0.1 µW/cm^2. Active antennas may improve the energy harvesting system efficiency. All antennas presented in this paper can operate also as passive antennas.

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A. Sabban (M'87-SM'94) received the B.Sc degree and M.Sc degree Magna Cum Laude in electrical engineering from Tel Aviv University, Israel in 1976 and 1986 respectively. He received the Ph.D. degree in electrical engineering from Colorado University at Boulder, USA, in 1991. Dr. A. Sabban reasearch interests are microwave and antenna engineering. In 1976 he joined the armament development authority RAFAEL in Israel. In RAFAEL he worked as a senior researcher, group leader and project leader in the electromagnetic department till 2007. In 2007 he retired from RAFAEL. From 2008 to 2010 he worked as an RF Specialist and project leader in Hitech companies. From 2010 to date he is a senior lecturer and researcher in Ort Braude College in Israel in the electrical engineering department. He published over 60 research papers and hold a patent in the antenna area. Dr. A. Sabban wrote two books on Low visibilty antennas and a book on electrmagnetics and microwave theory for graduate students. He also wrote two chapters in books on microstrip antennas.