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Capturing Surface Electromagnetic Energy into a DC through Single-Conductor Transmission Line at Microwave Frequencies

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Abstract—This communication demonstrates the feasibility of rectifying microwave energy through one-wire with no earth return. In the proposed transmission system, a novel coaxial to Goubau line transition (referred thereafter as coaxial/G-line transition) was employed to transfer microwave power from TEM modes in a coaxial line to TM modes in a Goubau line. The captured signal at the receiving end of the Goubau line can be either directly used for communication or rectified into a DC. The proposed system can be used as an emergency source of power supply for cable cars, escalators and window cleaning gondolas in the event of accidents. According to our experimental results, a 0 dBm microwave signal can be transmitted through a single conductor of 13 cm in length with an insertion loss of less than 3 dB. When the input power was raised to 15 dBm, the electromagnetic energy at the receiving end can be rectified at 1.36 GHz into a DC with the efficiency at approximately 12.7%.

1. INTRODUCTION

Emergency source of power is constantly required during an accident on a cable car, an escalator or a window cleaning gondola. During an accident, there may be a prolonged interruption of power supply to the people trapped inside a cable car, an escalator or a window cleaning gondola for several hours. The power to be required by the trapped individuals can be at least several million times the power of an RF signal received by a conventional cell phone. The DC voltage at the receiving end needs to be at least 3.7 volts, which is the minimum voltage required for charging up a typical cell phone. This voltage can come from several power sources connected in parallel or in series. In an urgent situation as such, wireless power transfer by magnetic coupling as proposed by MIT [1] can be practically impossible. It is virtually impossible to deliver such a large power over a long distance through the space using conventional RF communication technologies. The most convenient medium for communication or for power transfer is perhaps the steel cable hanging a cable car, an escalator or a window cleaning gondola, in which the trapped people might not even have enough battery life to talk on their cell phones. Undoubtedly, there is a serious demand for a mature technology involving single-conductor transmission of electricity with no earth return.

For the first time, this paper demonstrates the feasibility of capturing a microwave energy through a one-wire transmission line into a DC. There is no second conductor of any form in the proposed system. As opposed to the conventional twin-wire transmission system, in which both transverse electromagnetic (TEM) modes and transverse magnetic (TM) modes can coexist, a single-conductor transmission line can only transmit TM modes. These TM modes are excited by a displacement current which is widely believed to be unable to do any work. Propagation of TM modes on uncoated or dielectrically coated conductors have been shown to provide low attenuation, low radiations, low dispersion and high power handling at frequencies from microwave bands to terahertz frequencies [2–12].

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The proposed system is illustrated in Figure 1(b) and Figure 1(c). It comprises three parts: a coaxial/G-line transition, a Goubau line and an AC-DC rectification section. The efficiency of a multi-strand twisted cable has been dealt with in other literature [2–4]. In this work, a Goubau line was used to simulate the proposed system for one-wire power transfer [5–12] because a multi-strand twisted cable was overly bulky. The Goubau line has one end connected to a novel coaxial/G-line transition and the other end to two Schottky diodes connected in a back-to-front fashion. At microwave frequencies, the TEM mode electromagnetic waves are first converted by the proposed coaxial/G-line transition into TM mode electromagnetic waves, which are then delivered through the Goubau line. Finally, the TM mode electromagnetic waves are rectified into a DC using the Schottky diode pair.

2. GOUBAU LINE FOR SINGLE-CONDUCTOR POWER TRANSMISSION

The transmission line enabling the proposed one-wire power transfer is basically a enamel-coated copper wire, as shown in Figure 1(a), with the length l, cross-sectional diameter of the inner conductor a, thickness of the enamel coating $b - a$, and dielectric constant of insulated coating ε_d.

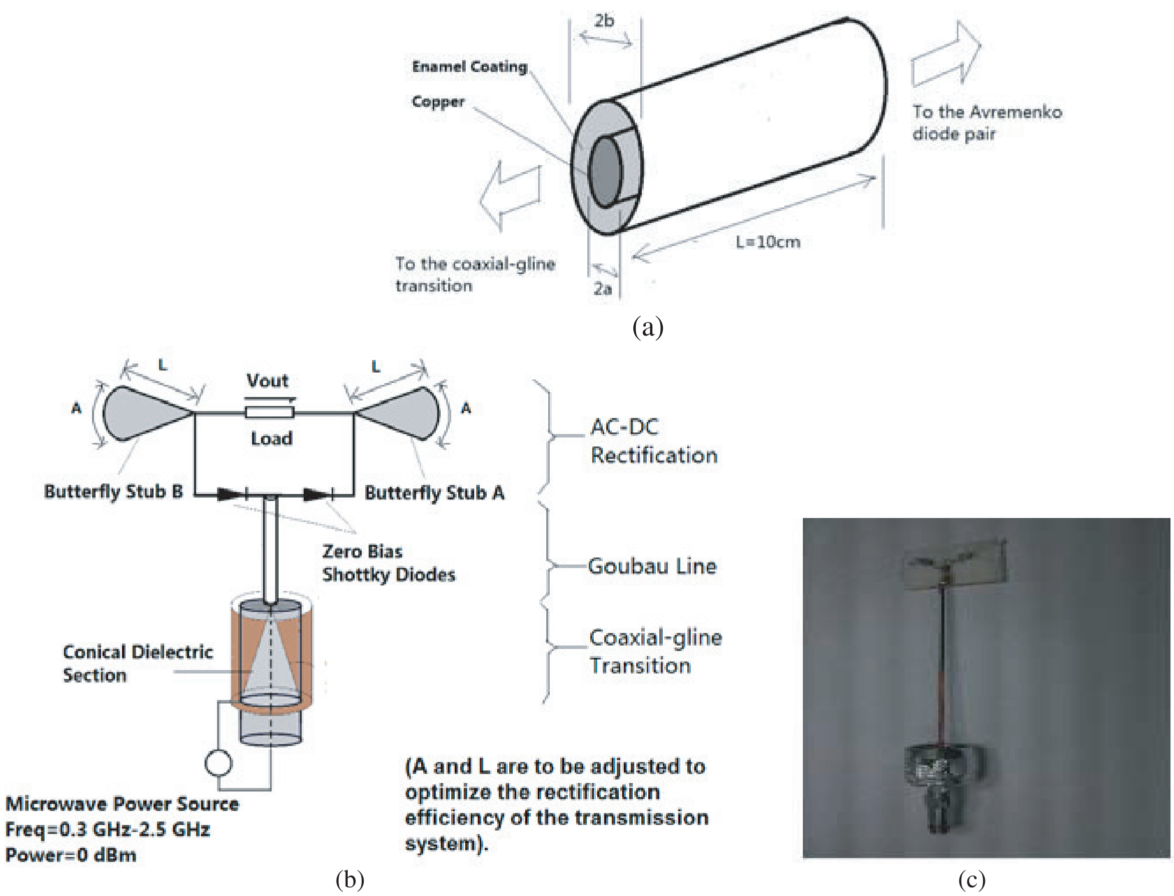


Figure 1. (a) Enamel coated Goubau line, with length = 10 cm, diameter of the central conductor = 1 mm and thickness of dielectric coating = 0.03 mm; (b) schematic of the proposed system for one-wire power transfer without any earth return; and (c) photograph of the final prototype.

Goubau line is claimed to be non-radiating. Despite the advantage of being non-radiating, the conductor losses in a Goubau line increase as the operating frequency increases. However, the conductor losses are inversely proportional to the square of line impedance, which is normally in excess of 500 ohm in Goubau line.

The overall attenuation of a Goubau line can be determined from the propagation constant. At frequency f, the surface electromagnetic wave travels at near the speed of light, c. The propagation constant of this Goubau line can be estimated using a modified version of the approximation formula proposed by Jaisson [13]:

$$k_z = k_0 \sqrt{1 + \frac{\varepsilon_d - 1}{1 + \varepsilon_d K_e / G}} \tag{1}$$

where

$$k_0 = \frac{2\pi f}{c} \tag{2}$$

$$K_e = 0.11593148 - \ln(-q)\ln(-\ln(-q)) + \frac{\ln(-\ln(-q))}{\ln(-q)} \tag{3}$$

$$q = \frac{\left(\frac{1}{\varepsilon_r} - 1\right)(k_0 b)^2 G}{3} \tag{4}$$

and

$$G = \left(1 - \frac{a}{b}\right)\left(6 + \left(1 - \frac{a}{b}\right)\left(5 - \frac{2a}{b}\right)\right) \tag{5}$$

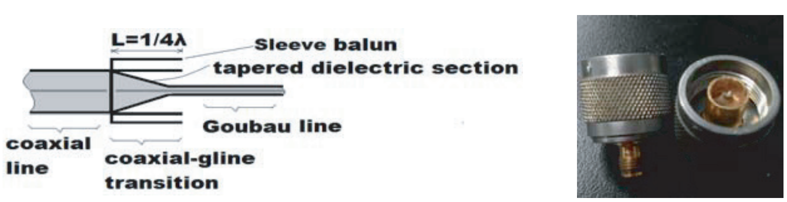
If only pure TM modes are allowed in the propagation modes, then the following constraint must be satisfied in order for Equation (1) to be used:

$$f < \frac{c}{2\pi b \sqrt{e} \sqrt{\left(1 - \frac{1}{\varepsilon_d}\right) \frac{G}{3}}} \tag{6}$$

Equation (6) suggests that, when the proposed system operates at frequencies higher than the maximum given by Equation (6), the leaky modes and the evanescent modes will take over.

3. COAXIAL TO GOUBAU LINE TRANSITION

The novel coaxial to Goubau line transition responsible for converting TEM modes from standard microwave or submillimeter wave instruments is shown in Figure 2. As suggested in Table 1, the proposed coaxial/G-line is superior to other published counterparts in terms of efficiency, maximum size as well as ease of fabrication. More attractive is the fact that it can be conveniently made out of a discrete balun. Constructing this coaxial/G-line transition does not require any step involving photolithography or micro-fabrication.



(a) (b)

Figure 2. (a) Cross-sectional view of the proposed coaxial/G-line transition. (b) Photograph illustrating the proposed coaxial/G-line transitions.

In the proposed coaxial/G-line transition, as shown in Figure 2(a), a central conductor extended from the end of a coaxial cable is completely encapsulated by a conical dielectric structure made with silicone. This conical dielectric section, also known as tapered dielectric section, is surrounded by an outer cylindrical ground extended from the end of the coaxial cable. Like other dipole antennas, the

Table 1. Comparison between the proposed coaxial/G-line transition and other published counterparts.

	Goubau's Launcher [12]	Gunn's Launcher [15]	This work
Maximun size	3λ	$\frac{1}{4}\lambda$	$> \frac{1}{4}\lambda$
Efficiency	63.8%	63%	Above 80% at microwave frequencies, according to our measurement
Easy to machine?	Involve CNC milling of curved surface	Not easy at all.	Can be constructed out of a discrete balun

cylindrical ground tends to radiate electromagnetic energy outwards. The radiation losses from the cylindrical ground appear to be the main reason why some other published coaxial/G-line transitions are relatively lossy. In the proposed coaxial/G-line transition, however, the cylindrical ground at the end of the coaxial cable is further shielded with a sleeve balun of roughly $\frac{1}{4}\lambda$ in length as to minimize the leaky modes from the cylindrical ground.

Figure 2(b) shows a photograph of the pair of the coaxial/G-line transitions constructed out of a TNC connector SM4766 manufactured by Fairview Microwave. We have used RTV silicone to make the conical structure for the tapered dielectric section, instead of Teflon, because of two reasons: a) the dielectric constants of RTV silicone and Teflon are similar; and b) curing RTV silicone does not require melting at high temperature.

4. POWER LOSSES DUE TO THE COAXIAL TO GOUBAU LINE TRANSITION

The attenuation of the proposed coaxial/G-line transition can be mathematically derived using Equation (1). Assume that the whole length of the conical section comprises N sub-sections connected in cascade. The length of each sub-section is given by, $\Delta l = l/N$, where l is the length of the conical section. If the conical section is linearly tappered, then we have, $N = (B-a)/\Delta b$, where B is the radius of the coaxial cable connected to the proposed coaxial/G-line transition. The expression of Δl can be rewritten as $\Delta l = l\Delta b/(B-a)$. The propagation coefficient at any particular point along the central axis of the conical section is then $\Delta l_z(b)$. If N trends to infinity, then the propagation constant of the conical section can be estimated as:

$$k_c = \frac{l}{B-a}\int_a^B k_z(b)db \tag{7}$$

where $k_z(b)$ can be computed using Equation (1).

5. CUTOFF FREQUENCIES

In the proposed coaxial/G-line transition, the tapered dielectric section involves curvature and non-smooth corners, which unavoidably excite higher order modes. The higher order modes are radiating, but they are well confined if the gap between the sleeve balun and the coaxial cable is minimized. These high order modes result in cut-off frequencies, which can be estimated using the following asymptotic formulae (8) as explained by Siart et al. [14].

$$\omega_{m,cutoff} = m\frac{\pi}{t_d}\frac{c}{\sqrt{(\varepsilon_d\mu_d - \varepsilon_o\mu_o)}} \tag{8a}$$

$$\omega_{m,cutoff} = \left(m+\frac{1}{2}\right)\frac{\pi}{t_d}\frac{c}{\sqrt{(\varepsilon_d\mu_d - \varepsilon_o\mu_o)}} \tag{8b}$$

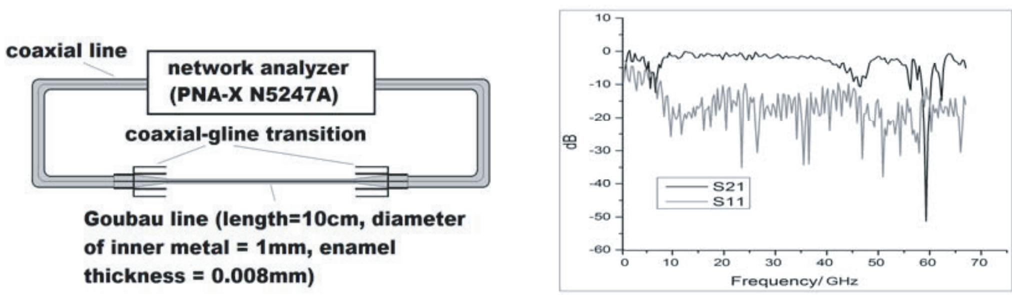
where m is the order of mode and t_d the dielectric thickness of a dielectrically coated Goubau line. ε_d and ε_o are respectively the dielectric constants of the enamel coating and free space. μ_d and μ_o are respectively the relative permeabilities of the enamel coating and free space. $\omega_{cutoff,m}$ is the cut off radian frequency.

6. RESULTS AND DISCUSSIONS

This section details the experimental setup and measured results for the Goubau line, coaxial/G-line transitions as well as the final single-wire rectification system.

The experimental setup for measuring the S-parameters of the proposed coaxial-line transition is illustrated in Figure 3(a). In the experimental setup, the media simulating power transfer through one-wire is a Goubou line having 13 cm long copper of cross-sectional diameter = 1 mm. The Goubou line was coated with a 0.008 mm thick enamel layer having dielectric constant in the neighborhood of 3. The Goubau line is connected to port 1 and port 2 of a network analyzer (Agilent Technologies, N5247A) through a pair of the proposed coaxial/G-line transitions. The two coaxial/G-line transitions do not have to share the same ground connection.

The design of the proposed coaxial/G-line transition has been optimized at two frequency ranges: from 10 MHz to 4 GHz and from 10 GHz to 30 GHz. The measured S-parameters as shown in Figure 3(b) shows that the S_{11} at frequencies from 10 GHz to 30 GHz is in general less than -18 dB. According to the measurement, the whole experimental setup dissipates less than 3 dB insertion losses at frequencies from 10 MHz to 4 GHz and 2 dB insertion losses at frequencies from 10 GHz to 40 GHz.



(a) (b)

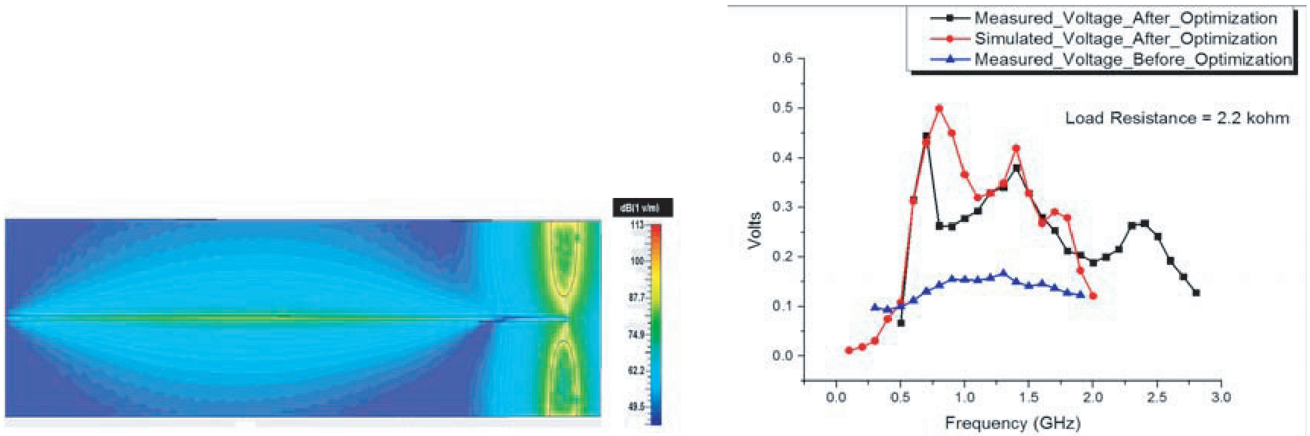
Figure 3. (a) Measurement setup for the proposed coaxial-G-line transition. (b) Measured S-parameters of the system involving the pair of coaxial/G-line Transitions and a Goubau line.

According Equation (1), the calculated insertion loss of the Goubau line is 0.825 dB at 2 GHz and 0.1684 dB at 10 GHz. After substracting the calculated losses of the Goubou line from the measured S_{21}, we found that the actual attenuation of each of the proposed coaxial/G-line transition was around 1.0875 dB at frequencies from 10 MHz to 4 GHz and around 0.9158 dB at frequencies from 10 GHz to 30 GHz. According to Equation (1), the computed attenuation of the proposed coaxial/G-line transition is 1.071 dB insertion loss at 2 GHz, corresponding to 88% in efficiency. The attenuation of the proposed coaxial/G-line transition derived from the measured S-parameters agrees well with the value calculated using Equation (8).

In our experimental setup, the conical dielectric section of the proposed coaxial/G-line transition is linearly tapered with the largest thickness being the outer diameter of the coaxial cable (i.e., approximately 3.75 mm). The dielectric constant of RTV silicone rubber is 3.6. According to Equations (8a) and (8b), the first order cut-off frequency should be 49.8 GHz, corresponding to the band rejection found at 48 GHz as shown in the measured S-parameters.

In the proposed one-wire microwave power transfer system, the frequency range from 1 GHz to 4 GHz is chosen in this work to study the feasibility of rectification through a one-wire transmission line because this frequency band can be used to transmit signals from cell phones.

The experimental setup demonstrating the single conductor transmission system is shown in Figure 1(b). The receiving end of the Goubau line is connected to a pair of zero-bias Schottky diodes (SMS7621-079LF) in a back-to-front fashion proposed by Avramenko [16], with an exception that a butterfly stub was added to each terminal of the load as an open-circuit stub to maximize the voltage across each diode. Avramenko's diode arrangement is supposed to be fed with an AC voltage in the order of thousand volts, while the proposed one-wire system can operate at a power as low as -10 dBm. To optimize the circuit performance, the arc A and the radius L of the butterfly stubs A and B are



(a) (b)

Figure 4. (a) Electric field distribution of the rectification section simulated using CST Studio Suite. (b) Load voltage measured against frequency when the load resistance = 2.2 kOhm and when the input power = 0 dBm.

individually adjusted in CST Studio Suite$^{\mathrm{TM}}$ until the potential difference across each of the diodes is maximized. In theory, the radius L should be equivalent to a quarter electrical wavelength. Figure 4(a) shows the electric field distribution of an optimized rectification section obtained by CST simulation.

Figure 4(b) shows the load voltage measured against operating frequency when the input power is maintained at 0 dBm. It was found that, before the optimization, a maximum of 1.02% efficiency at around 0.9 GHz. After optimizing the geometry of each butterfly stub and the overall circuit topology, a maximum of 0.37 volts was measured at the load at around 1.36 GHz, corresponding to 6.22% in efficiency (See Figure 4(b)). At this frequency, the input power has been further adjusted in order to boost the overall efficiency. A 12.7% efficiency was finally obtained at 1.36 GHz when the input power was raised to 15 dBm. However, the overall efficiency has significantly decreased when another pair of less efficient diodes were used, possibly because of the impedance mismatch.

The broadband and low loss features of a single-conductor transmission system are obvious in the measured S-parameters as shown in Figure 3(b). It is even suggested that a microwave signal can be efficiently transmitted over a long distance in a single-conductor transmission system [17–19]. However, because of the intrinsic resistance in the Schottky diodes, most of the transmitted power was lost in the AC-to-DC rectification section. Whilst the geometries of the butterfly stubs can be adjusted to optimize the overall performance, the intrinsic performance of each diode cannot be changed. Fortunately, the proposed system can be inexpensively implemented. As far as the cost of implementation is concerned, the proposed AC-to-DC rectification of microwave energy remains an acceptable choice for emergency power supply.

In the proposed system, the rectification section rectifies a microwave power in half-wave rectification. If the peak voltage of the electromagnetic wave is V_p, then the DC power that can be delivered to the load R will be no more than $V_p^2/(\pi^2 R)$, as opposed to $16V_p^2/(\pi^2 R)$ in the case of a full-wave rectification. A higher DC output power can be achieved by full-wave rectification. Full-wave rectification of TM modes necessitates another input fed directly from a virtual ground. This issue is, however, beyond the scope of this paper.

The maximum power handling capacity of the proposed system depends on two factors: a) the power carrying capacity of the dielectrically coated Goubau line and b) the power handling capacity of the rectification section. Goubau line is more vulnerable to thermal stress due to the current than to electrical stress due to the dielectric breakdown. Since the cross-sectional diameter of the Goubau line in the proposed system is 1 mm, the maximum transmissible power should be approximately 100 kW, according to Reference [20]. This power should be enough for a full duplex communication. As for AC-to-DC rectification, the maximum power depends on the ratings of the diodes. For example, one of the power Schottky diodes from ST-Thomson can handle a maximum of 48 kW.

At millimeter-wave frequencies or above, however, Schottky diodes are not the best option for AC-to-DC rectifications. By far, metal-insulator-metal tunnelling or geometrically asymetrical tunnelling approach are the only options appropriate for terahertz or optical rectification [21, 22]. Perhaps, more research needs to be devoted to these areas.

7. CONCLUSIONS

In conclusion, our experimental results suggest that single-wire power transfer without any ground connection is technically feasible at microwave frequencies. The proposed system which simulates one-wire microwave power transfer has a dielectrically coated Goubau line with one end connected to a novel coaxial/G-line transition and the other end to a pair of Schottky diodes arranged in a fashion proposed by Avramenko [16]. Unlike the diode arrangement proposed by Avramenko, which needs to be fed with an AC power in the order of thousand volts, the proposed single-wire system was found to be able to capture a 15 dBm microwave power into a DC with an efficiency at 12.7%. The coaxial/G-line transition was found to be able to convert electromagnetic TEM modes from a coaxial cable to TM modes in a Goubou line with an insertion loss 1.087 dB. The measurement agrees with the figures calculated using derived equations. In general, the microwave power was efficiently transmitted in the Goubau line and the coaxial/G-line transition, but most of the delivered power was lost in the AC-DC rectification.

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