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A Wearable All-Printed Textile-Based 6.78 MHz 15 W-Output Wireless Power Transfer System and its Screen-Printed Joule Heater Application

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Abstract—While research in passive flexible circuits for Wireless Power Transfer (WPT) such as coils and resonators continues to advance, limitations in their power handling and low efficiency have hindered the realization of efficient all-printed high-power wearable WPT receivers. Here, we propose a screen-printed textile-based 6.78 MHz resonant inductive WPT system using planar inductors with concealed metal-insulator-metal (MIM) tuning capacitors. A printed voltage doubler rectifier based on Silicon Carbide (SiC) diodes is designed and integrated with the coils, showing a power conversion efficiency of 80-90% for 2-40 W inputs over a wide load range. Compared to prior wearable WPT receivers, it offers an order of magnitude improvement in power handling along with higher efficiency (approaching 60%), while using all-printed passives and a compact rectifier. The coils exhibit a simulated Specific Absorption Rate (SAR) under 0.4 W/kg for 25 W received power, and under 21°C increase in the coils' temperature for a 15 W DC output. Additional fabric shielding is investigated, reducing harmonics emissions by up to 17 dB. We finally demonstrate a wirelessly-powered textile-based carbon-silver Joule heater, capable of reaching up to 60°C at 2 cm separation from the transmitter, as a wearable application which can only be wireless-powered using the proposed system.

Index Terms—Antennas, Coils, Heaters, Inductors, Rectifiers, Resistors, RFID, Wireless Power Transfer.

I. INTRODUCTION

FLEXIBLE wearable systems represent the closest sensing and actuation platform to the user [1]. Emerging wearable sensing systems [2]–[4], antennas [5], and body area networks [6] have mostly been implemented using flexible or

textile-based materials, for seamless integration into clothing. It is widely recognized that conventional batteries are not a wearable-friendly option [1], [7]–[9], leading to research efforts seeking a solution in wireless power transfer (WPT) [9]–[12] and in flexible or wearable energy harvesters [7], [13].

While low-power wearable sensors can be powered using far/mid-field WPT [14], wearable applications such as Joule heaters [15] or mobile neural network classification processors, sampling wearable sensors [16], cannot be powered using any of the reported wearable textile-based energy harvesting or WPT solutions. To explain, wearable mid/far-field WPT solutions are focused on μW to mW applications [9], [17], [18]. Moreover, wearable and implantable near-field WPT research is mostly focused on the passive electromagnetic link [11], [19]–[21], with no flexible or textile-based rectifiers designed and optimized for wearable or large-area electronics.

Individual additively-manufactured passive components, however, show promise for all-printed WPT receivers. For example, inkjet printed RLC circuits have been reported on smooth thin films, handling around 100 mW [22]. Furthermore, printed capacitors on rough textile substrates have recently been demonstrated with better microwave power-handling (up to 1 W) than their discrete ceramic counterparts [23]. Printed textile-based coils were integrated with rigid FR4-based Qi-standard circuitry in [24] and demonstrated receiving around 1.5 W with a 37% DC-DC efficiency. In [25], we demonstrated a 3.75 W 6.78 MHz WPT receiver based on a flexible rectifier and resonant embroidered coils. However the WPT system in [25] had several limitations which cannot be solved using existing flexible and wearable WPT implementations including: (a) low power-handling capability of compact (<1 cm) surface-mount tuning capacitors, (b) low efficiency of the rectifier due to the high switching speed and the small form-factor, (c) high thermal losses with a peak temperature exceeding 200°C, and (d) unreliable packaging due to using multiple fabrication processes (embroidered coils, copper-based rectifier), and the surface mismatch caused by the flexible-rigid interface between the tuning rigid capacitors and the coils. Therefore, there has been no work to date demonstrating the feasibility of efficient ($>50\%$) and high-power (>3 W) WPT using all-flexible resonators and power conversion circuits.

In this paper, we propose a printed textile-based wirelessly-powered system which addresses the outstanding challenge

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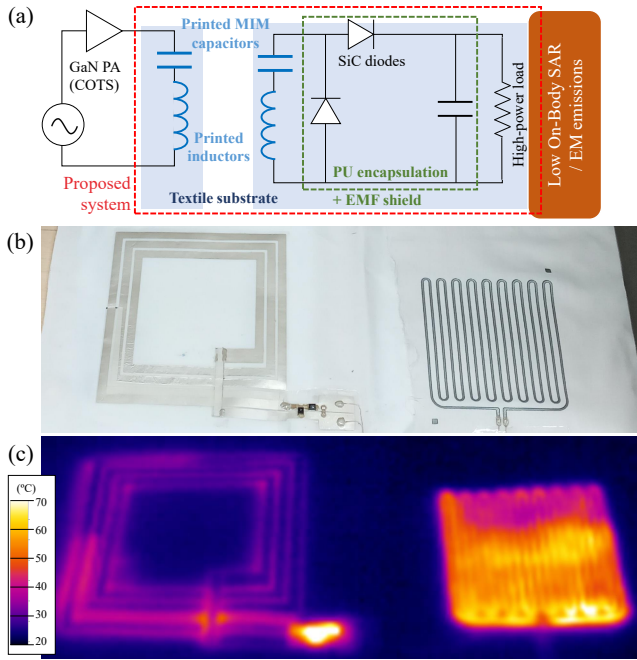


Fig. 1. Overview of the proposed high-power wearable WPT: (a) High-level schematic of the system; (b) photograph of the integrated system; (c) thermal image showing the system's operation.

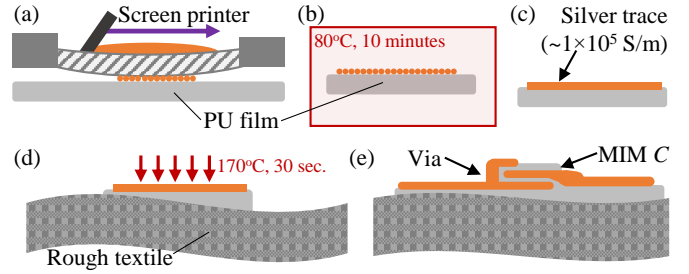


Fig. 2. Fabrication steps of the textile-based coils: (a) printing the conductors on the transfer layer; (b) initial curing; (c) the dried silver adhesive (PU)-backed film; (d) heat-transfer onto a textile substrate ; (e) the assembled structure.

coil in the photograph, driven by a Commercial-Off-The-Shelf (COTS) GaN power amplifier (PA) demonstration kit (GSWP050W-EVBPA). 107
108
109

A. Fabrication Method and Material Characterization 110

Instead of directly screen printing on the substrate, e.g. 111
rough fabrics, the conductors are printed on a smooth 75 μm - 112
thick polyurethane (PU) film, which is then heat-pressed 113
onto the fabric, as in Fig. 2(a) to (d). To explain, fabric 114
typically requires blanket coated textiles or the prior screen 115
printing of specialist interface layers [26], and can limit curing 116
temperatures. We have previously shown that by printing on 117
the PU film, the printed traces can withstand over 10,000 118
bending cycles and can be applied to different textiles regard- 119
less of their roughness [23]. For WPT applications at kHz 120
frequencies, printed coils could be fabricated with Litz-like 121
geometries using the same process [27]. 122

By laminating multiple PU/silver layers onto the textile, 123
metal-insulator-metal (MIM) capacitors can be realized, as in 124
Fig. 2(e), which can be used to tune the coils. These capacitors 125
exhibit improved mechanical reliability over their inkjet coun- 126
terparts [22], [28], which are restricted to smooth polymers and 127
thin conductors. The large-area printed capacitors can achieve 128
higher power handling than discrete ceramic capacitors. Once 129
the circuit is printed, the components are attached using 130
conductive epoxy, cured at 90°C, then encapsulated using a 131
PU superstrate for mechanical reliability. 132

Following the calculation [29] or measurement of the 133
printed coils' inductance, detailed in Section II-B, the tuning 134
capacitor can be integrated on the same substrate. To realize 135
tuning capacitors C for resonant WPT, C is given by 136

$$C = \frac{1}{4\pi^2 f_r^2 L} = \epsilon_{\text{PU}} \frac{W_c L_c}{t} \quad (1)$$

where $f_r=6.78$ MHz, ϵ_{PU} is the permittivity of the PU film 137
at 6.78 MHz, in Fig. 3, $t=55$ μm , the measured height of the 138
heat-pressed dielectric, with L_c and W_c representing the length 139
and width of the integrated tuning capacitor, respectively, as 140
shown in Fig. 5(a). 141

The relative permittivity of the heat-pressed PU laminates 142
was measured using a test MIM capacitor of known dimen- 143
sions. The capacitance was measured using a Wayne Kerr 144
6500 impedance analyzer between 100 Hz and 10 MHz, which 145

77 of high-power wearable WPT, that is the realization of an 78
all-flexible WPT receiver. First, the design and fabrication of 79
screen-printable resonant coils, suitable for integration on any 80
textile substrate is presented (Section II), achieving up to 70% 81
link efficiency (Section III). The coils are integrated with a 82
flexible textile-based >90%-efficient voltage doubler, using 83
off-the-shelf diodes, receiving over 14 W with an end-to-end 84
efficiency of 60% (Section IV-A and B), and is demonstrated 85
powering a printed heater with over 2 cm range (Section IV- 86
C).

II. ALL-PRINTED COILS DESIGN AND FABRICATION 87

88 To enable textile-integrated WPT to supply high-power 89
wearable applications, such as the Joule heater presented 90
here, the system illustrated in Fig. 1 is proposed. A typical 91
printed e-textile heater consumes over 1 W of DC power [15], 92
implying that existing wearable WPT systems cannot power 93
these directly and must instead charge a battery which in turn 94
periodically supplies the textile heater.

95 The coils and their tuning capacitors are realized using an 96
inexpensive screen printing and lamination process, detailed in 97
the next section, enabling them to achieve higher power han- 98
dling than prior work utilizing discrete components [25]. The 99
rectifier is seamlessly integrated on the same textile substrate 100
and encapsulated for mechanical reliability. Both textile-based 101
and conventional transmitter coils are characterized, using 102
small-signal s-parameters, investigating the potential for WPT 103
transmitters being integrated in non-wearable and industrial 104
textiles used in furnishings (e.g.s chairs). Fig. 1(b) and (c) 105
show the complete system being wirelessly-powered using 106
a textile-based transmitting coil, placed beneath the visible

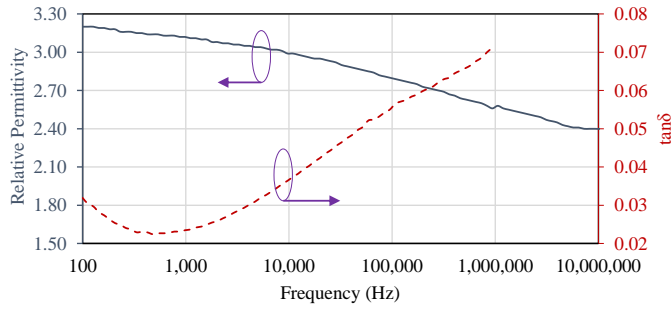


Fig. 3. Measured real relative permittivity and $\tan\delta$ of the 55 μm -thick pressed PU with silver conductors.

146 is lower than the capacitor's self-resonant frequency (SRF).
 147 Fig. 3 shows the calculated $\Re\{\epsilon_r\}$ of the PU laminate, where
 148 it can be seen that the PU maintains $\Re\{\epsilon_r\}=2.4$ at 6.78 MHz.

149 B. Coil, Capacitor, and Rectifier Design

150 Four square coils of varying sizes were designed. The
 151 inductance of the coils was approximated using the modifier
 152 Wheeler formula by Mohan *et al.* for printed inductors [29].
 153 The uniform square geometry was chosen due to its simple
 154 closed-form analysis [30] and its wide adoption in flexible and
 155 printed electronics [31]. Table I summarizes the geometrical
 156 and electrical parameters of each coil, along with their measured
 157 inductance; the layout of a 3-turn ($n=3$) coil is shown
 158 in Fig. 5(a), where the laminated capacitor can be observed.
 159 In a 1:1 WPT link, the mutual inductance L_M between planar
 160 coils could be calculated using the solution to the Neumann's
 161 integral for the current over the coils, by Raju *et al.* [30] as

$$L_M = \frac{\mu}{4\pi} \oint_{C_{TX}} \oint_{C_{RX}} \frac{dl_{TX} dl_{RX}}{s}, \quad (2)$$

over the coil's surface. The total L_M can be expressed as

$$L_M = \rho \times \sum_{i=n_{TX}}^{i=1} \sum_{j=n_{RX}}^{j=1} M_{ij} \quad (3)$$

$$L_{M,ij} = \frac{\mu_0 \pi a_i^2 b_j^2}{2(a_i^2 + b_j^2 + d^2)} \left(1 + \frac{15}{32} \gamma_{ij}^2 + \frac{315}{1024} \gamma_{ij}^4 \right) \quad (4)$$

$$a_i = b_i = D/2 - (n_i - 1)(w + s); \quad \rho = \frac{4}{\pi^2} \quad (5)$$

162 with d being the separation between the coils.

163 Along with the printed coils and tuning capacitors, a flexible
 164 textile-based rectifier is integrated on the same substrate. The
 165 rectifier is a voltage doubler based on a Silicon Carbide (SiC)
 166 Schottky diode (GB01SLT12-214). This diode was chosen due
 167 to its low resistance and capacitance enabling a high RF to
 168 DC power conversion efficiency (PCE) and low thermal losses.
 169 Moreover, the diodes have a reverse break-down voltage of 1.2
 170 kV. It was observed in [25] that a rectifier based on Silicon
 171 diodes with higher series resistance and 600 V breakdown
 172 voltage resulted in a PCE under 40%, and a temperature
 173 exceeding 200°C, limiting the power handling. A voltage
 174 doubler topology was chosen to enable a high voltage output
 175 that could, for example, directly power a wearable heater
 176 (as detailed later) without DC-DC conversion, as well as to

TABLE I
 SUMMARY OF THE COILS' PARAMETERS

Coil	Calc. L (μH)	Meas. L , 6.78 MHz	Meas. R , 6.78 MHz	w (mm)	s (mm)	D (mm)	n
A	1.40	1.60 μH	5.2 Ω	10	2.5	150	3
B	1.71	1.56 μH	6.4 Ω	5	2.5	120	3
C	1.98	2.03 μH	9.5 Ω	2.5	2.5	105	3

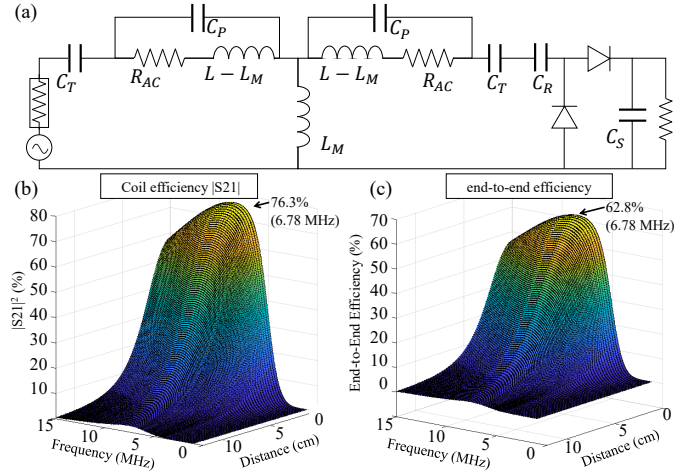


Fig. 4. (a) equivalent circuit model of the WPT system (b) analytical link efficiency over frequency and separation; (c) end-to-end efficiency as a function of frequency and separation.

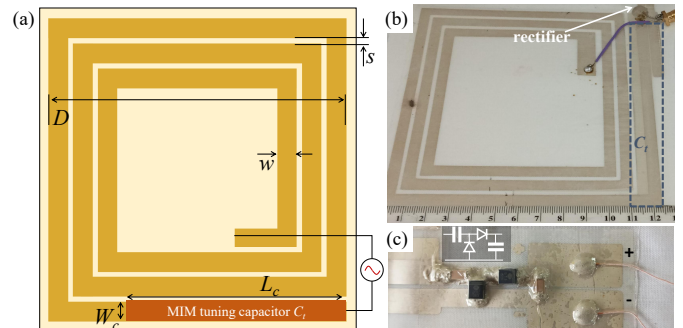


Fig. 5. (a) Generic layout of the coils showing the key dimensions; (b) photograph of coil A; (c) schematic and photograph of the rectifier showing the encapsulation and coils interface.

177 reduce the component count. This reduces the packaging and
 178 layout complexity and overall cost, improving the system's
 179 robustness. The simulated and measured DC output of the
 180 rectifier is presented in Section IV-A-A.

181 Using the calculated L_M , an equivalent circuit model com-
 182 bining the coupling of the coils and the rectifier based can
 183 be constructed [10], as shown in Fig. 4(a). The coupling
 184 efficiency of the coils was analytically calculated as the $|S_{21}|^2$
 185 of the circuit, assuming the rectifier is replaced with an ideal
 186 50 Ω load for varying d and frequency and is shown in
 187 Fig. 4(b), for $L=1.41 \mu\text{H}$, $R_{AC}=5.4 \Omega$, representing coil A
 188 from Table I. For the maximum coupling between the coils,
 189 i.e. at minimum separation, the circuit parameters in Fig. 4(a)
 190 are $C_T=393 \text{ pF}$, $R_{AC} = 4 + f^{1.36}/1 \times 10^{-10} \Omega$, $C_P=10$
 191 pF , $(L - L_M)=0.52 \mu\text{H}$, $L_M=1.09 \mu\text{H}$, $C_R=1 \text{ nF}$, $C_S=1 \text{ nF}$.
 192 The AC resistance was obtained using the fitted frequency-

193 dependence of the printed silver, where the high-frequency
 194 resistance increases due to the surface roughness of the inks;
 195 the supplementary material show the equivalent circuit model
 196 parameters for all fabricated coils. The diodes' model was
 197 based on the datasheet parameters.

198 The small-signal coil efficiency was calculated based on
 199 the equivalent circuit model and is shown in Fig. 4(b), for
 200 varying separation and frequency. To calculate the end-to-
 201 end efficiency of the system, non-linear harmonic balance
 202 simulation was used to calculate the rectifier's efficiency, with
 203 the amplifier's efficiency assumed to be 90%, as an average
 204 of its large-signal efficiency based on the vendor's datasheet.
 205 The end-to-end efficiency was calculated as $\eta = \eta_{PA} \times |S_{21}^2 \times$
 206 $\eta_{rect.}(P)$, where the rectifier's efficiency $\eta_{rect.}$ is a function
 207 of the input power, due to the rectifier's non-linearity. This
 208 is reflected in the closed-form calculation using a curve-fitter
 209 function, made available in the article's dataset. The rectifier's
 210 efficiency is assumed to be constant over frequency, as it varies
 211 by under 3% in the non-linear simulation. Fig. 4(c) shows
 212 the calculated large-signal end-to-end efficiency, for an input
 213 power level exceeding 10 W.

214 While the diode used is not flexible or printable, exist-
 215 ing solution-processed Schottky diodes cannot support the
 216 required power levels beyond 1 W [32]. The flexibility of
 217 the circuit can be improved by using a bare-die component
 218 on a thinned chip, making it more bendable [33], where the
 219 reliable integration of bare-dies within e-textiles has previously
 220 been demonstrated [34]. The rectifier was encapsulated using
 221 a conformable pressed PU film, improving the mechanical
 222 reliability and isolating the conductive traces from the user.

223 III. SMALL-SIGNAL COIL AND LINK CHARACTERIZATION

224 The coil parameters were measured using the VNA from 1
 225 to 10 MHz, and are shown in Fig. 6. The calculated response
 226 of the fitted equivalent circuit model are shown alongside the
 227 measured response; the equivalent circuit model's parameters
 228 are shown in the paper's supplementary material. The coil
 229 parameters are compared to the analytical L in Table I. A
 230 Rohde & Schwarz ZVB4 Vector Network Analyzer (VNA)
 231 was used to measure the s-parameters of the coils under
 232 varying separation and misalignment. SMA connectors were
 233 added to the resonant coils with the concealed capacitors
 234 to interface with the VNA, as shown in Fig. 5(b). The
 235 measured Q-factor (under 5 around 6.78 MHz) is comparable
 236 to previously reported printed coils implemented on smooth
 237 films [22], [35], showing that printing on the PU first and then
 238 laminating on to the textile does not affect coil properties.

239 The s-parameters of the one-to-one link, based on the
 240 printed coils, were simulated in CST Microwave Studio and
 241 measured using the VNA. Fig. 7 shows the simulated and
 242 measured s-parameters of the one-to-one link based on coils
 243 A and C, in close agreement. The conductivity of the coils
 244 was modelled as $\sigma=1 \times 10^4$ S/m. From the S_{11} response, it
 245 can be seen that the coils are matched ($S_{11} < -10$ dB) for
 246 separations under 2 cm, which is attributed to their relatively
 247 low inductance.

248 The s-parameters of the printed WPT coils were then
 249 characterized with a standard wire coil representing a non-

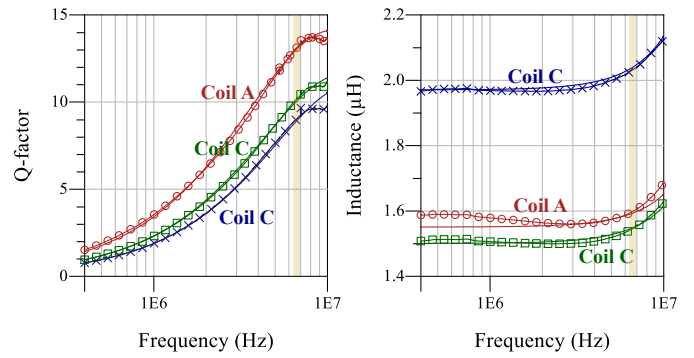


Fig. 6. Measured (markers) and calculated (solid line, no markers) equivalent circuit model's broadband inductance and Q-factor of the printed coils before integrating the tuning capacitors.

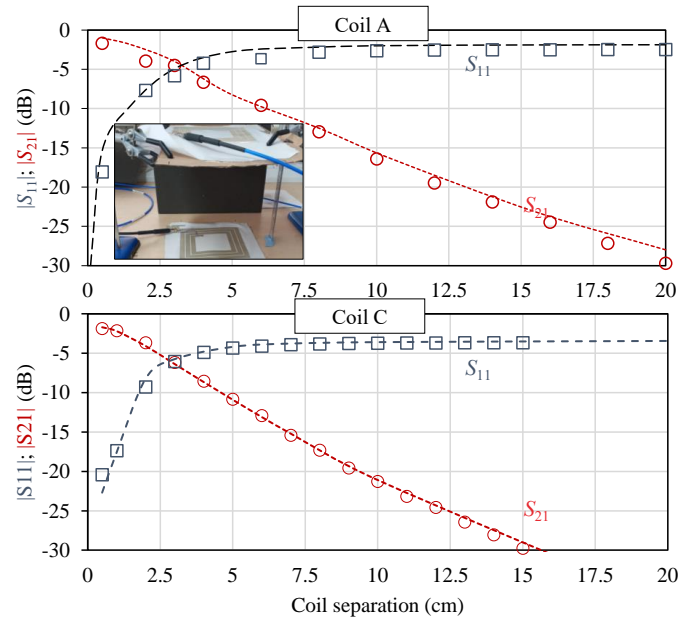


Fig. 7. Simulated (dashed line) and measured (solid markers) s-parameters of the symmetric link using coils A and C over varying distance; the inset shows the measurement setup.

250 textile transmitter. The coil is fabricated using a stranded
 251 wire of 1.5 mm² area, to act as a reference transmitter coil.
 252 The wire coil is composed of 5 turns, $D=15$ cm and has an
 253 inductance of 5.2 μH inductance, and 70 mΩ series resistance
 254 at 6.78 MHz. The forward transmission (S_{21}) between textile-
 255 based coils and the Litz coil was characterized for varying
 256 vertical separation as well as lateral misalignment. Fig. 8
 257 shows the measured S_{21} as a function of vertical separation.
 258 To investigate the influence of the printed capacitor on the link,
 259 the s-parameters of coil C were also measured with a discrete
 260 ceramic tuning capacitor alongside the printed capacitor.

261 From Fig. 8, it can be seen that there is minimal influence
 262 on the S_{21} from using the printed capacitor. Moreover, the
 263 S_{21} variation with vertical separation is directly linked to the
 264 coil's radius, which is attributed to the effect of the gap on the
 265 mutual inductance [30]. Frequency-splitting and over-coupling
 266 [10] are not observed due to their relatively low Q-factor
 267 of the coils. The effect of lateral misalignment on the S_{21} ,

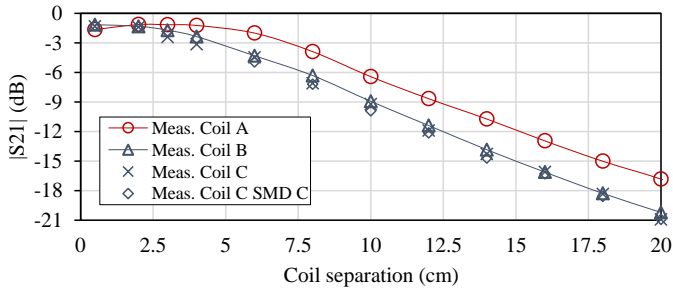


Fig. 8. Measured forward transmission between the textile coils and the reference wire transmitter over varying coil separations.

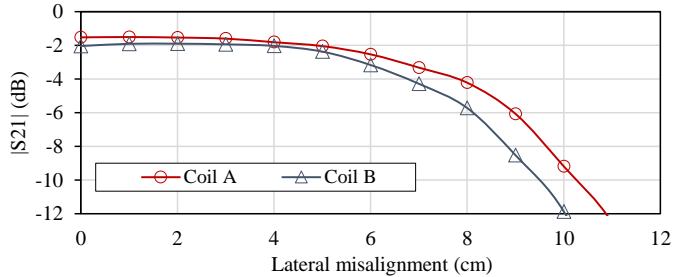


Fig. 9. Measured forward transmission between the textile coils and the reference wire transmitter over varying coil misalignments.

268 shown in Fig. 9, is directly related the coils' radii and the
 269 relative misalignment between the transmitting and receiving
 270 coil areas.

271 It is noted that the use of different coil geometries [36]
 272 or intermediate resonant coils or "meta-surfaces" can improve
 273 the link efficiency [11], [37]. However, the main focus of this
 274 work is to demonstrate a high-power WPT-enabled wearable
 275 system using all-printed passives, which to date has primarily
 276 been hindered by the rectifiers' or resonators' power handling
 277 as opposed to efficient resonator design.

278 IV. HIGH-POWER WPT CHARACTERIZATION

279 A. Rectifier Simulation and Measurements

280 The rectifier was simulated in Keysight ADS using harmo-
 281 nic balance simulation. The diode's parameters were taken
 282 from the datasheet and the 1 nF charge-pumping and smooth-
 283 ing capacitors were assumed to be ideal. A connectorized
 284 prototype of the proposed rectifier was fabricated for experi-
 285 mental validation. A load sweep was performed to identify
 286 the optimum load impedance Z_L in the >1 W power range;
 287 the rectifier maintains over 90% of its peak RF-DC efficiency
 288 for Z_L between 250 and 300 Ω . To characterize the rectifier
 289 under high power levels, the rectifier was connected directly
 290 to the 50 W PA demonstration kit's output and the PA's supply
 291 voltage was varied.

292 The input RF power was calculated using the PA's datasheet
 293 peak efficiency of 91% for a conservative estimate of the recti-
 294 fier's performance. Fig. 10 shows the simulated and measured
 295 DC output and efficiency of the rectifier for varying RF inputs
 296 up to the PA's maximum output. Despite its flexible and low-
 297 cost implementation, the rectifier can generate up to 35 W

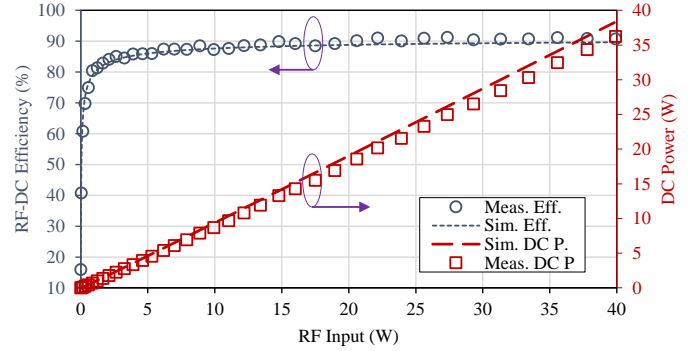


Fig. 10. Simulated and measured PCE and DC voltage output of the rectifier across a 261 Ω load.

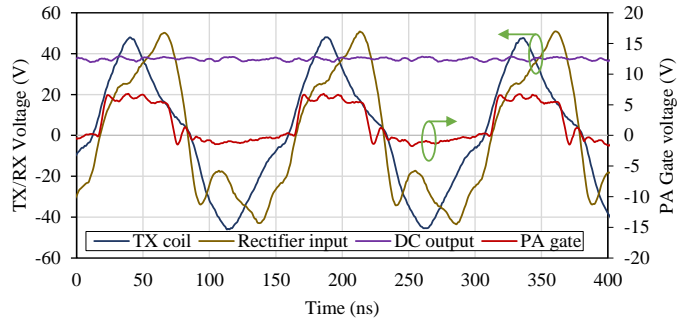


Fig. 11. Time-domain waveforms across the gate driver, transmitting and receiving coils, and the load.

298 DC output with an efficiency over 80% for inputs exceeding
 299 1 W. This represents over 20 \times improvement over previously
 300 reported WPT rectifiers reported for wearable (Qi) applications
 301 [24], where the system's output was limited to 1.51 W, or
 302 operating at higher frequencies for near-field charging of
 303 textile-based devices [17].

304 B. Coil and System Characterization

305 The rectifier's layout was integrated with the MIM capacitor
 306 and the screen-printed coils on a single substrate, as seen
 307 in Fig. 1(b). Coil A (having the largest dimensions and
 308 Q-factor) was used to characterize the full WPT system.
 309 Two identical coils were used for transmitting and receiving,
 310 thereby enabling the power handling ability of the textile coil
 311 to be investigated.. The separation between the two coils has
 312 been kept under 5 mm, formed by the textile substrates and
 313 a non-uniform air gap due to the coils' flexibility. In this
 314 configuration, the coils maintained an $S_{21} = -1.7$ dB translating
 315 to a WPT link efficiency of 67%. Combined with the rectifier's
 316 efficiency of approximately 90% and the PA's DC-RF effi-
 317 ciency exceeding 91%, an end-to-end efficiency between 55%
 318 and 60% could be expected depending on the PA and rectifier's
 319 power-dependent performance. Fig. 11 shows the time-domain
 320 voltage waveforms across the coils, the gate driver, and the
 321 load, when the coils are approximately 1 cm apart driven at
 322 10 W DC input.

323 To evaluate the system's power handling, the DC input to
 324 the PA was varied for a fixed coil separation of approximately
 325 5 mm. Fig. 12 shows the measured end-to-end system effi-

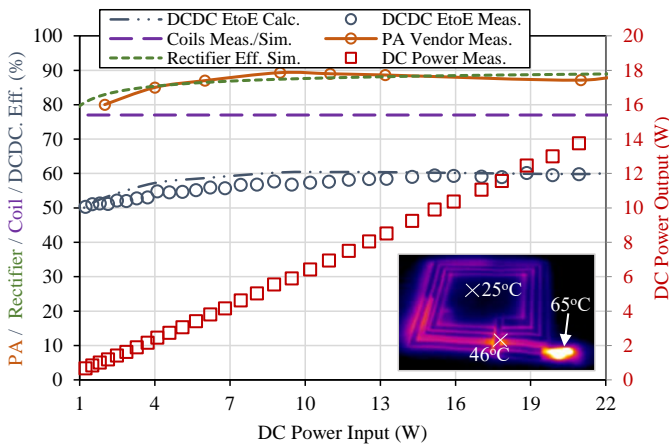


Fig. 12. Measured DC output of a small gap (<0.5 cm) wireless gap, the end-to-end DC-DC efficiency, and a break-down of the individual component efficiencies as a function of the DC input; the inset shows the system's temperature when driven at 22 W.

326 ciency and the DC power delivered to the load as a function
 327 of the DC input. The end-to-end efficiency was also calculated
 328 using the coils' simulated efficiency (assumed to be linear and
 329 is in close agreement with the measurements as in Fig. 7),
 330 the rectifier's simulated efficiency, and the PA's datasheet
 331 efficiency measured by the vendor. Both the calculated and
 332 measured DC-DC end-to-end efficiencies are shown in Fig. 12,
 333 showing a close agreement and indicating that the coils (due
 334 to their series resistance) have the lowest efficiency in the
 335 system. The maximum DC input of 21 W was limited by the
 336 PA's current draw at maximum bias, which could be further
 337 increased through adaptive impedance matching or using multiple
 338 loads. However, as this work focuses on the coil, power
 339 conversion, and load implementation, such optimizations were
 340 not explored.

341 From Fig. 12, it can be seen that the maximum expected
 342 efficiency of 60% is approached for high input power levels,
 343 and that the end-to-end efficiency exceeds 50% for inputs
 344 exceeding 1.5 W. At its maximum DC power output of 14 W,
 345 a 60 V potential was measured across the 261 Ω 100 W-
 346 rated dummy load. To explore the coils' power handling, an
 347 infrared (IR) thermal camera (Testo 875i) was used to observe
 348 the temperature over the receiving coil.

349 The inset in Fig. 12 shows the peak temperatures measured
 350 over the receiving coil's surface while being driven at a 21 W
 351 DC input, where a maximum temperature rise of 21°C is
 352 observed over the coil, and around 40°C rise is recorded at
 353 the rectifier. The higher temperature increase over the rectifier's
 354 surface is attributed to the diodes' series resistance being
 355 confined to their very small footprint, resulting in lower heat
 356 dissipation. However, the proposed rectifier and tuning capacitor
 357 reduce the temperature rise over prior flexible rectifiers,
 358 which could not operate above 4 W due to the temperature
 359 rising above 180 °C [25]. The observed peak temperature of
 360 65° falls within the diodes' specified operation range and is
 361 also lower than the curing temperature of the printed silver
 362 traces, implying no damage to either component. The system
 363 was driven at 22 W for over five minutes with no noticeable

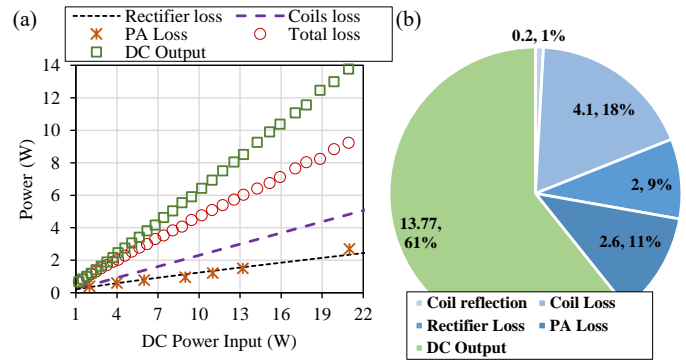


Fig. 13. Power loss analysis: (a) the measured DC output and the simulated/calculated losses at each stage for varying DC inputs; (b) the measured losses for Fig. 12 when driven at 22 W.

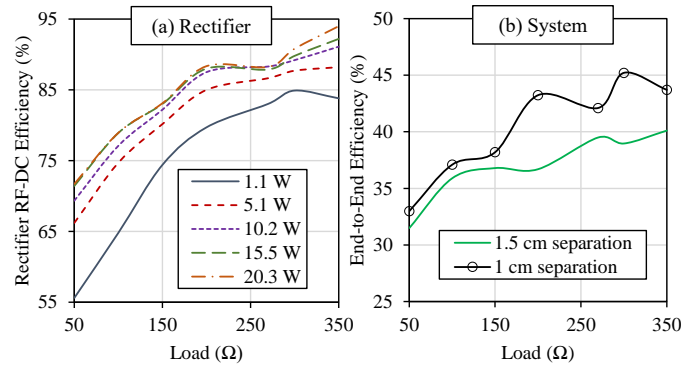


Fig. 14. Effect of varying load impedances on the efficiency: (a) RF-DC rectifier efficiency; (b) end-to-end WPT efficiency.

364 change in the voltage waveforms or the temperature profile.

365 The power losses in the system have been quantified using
 366 both the calculations and the measurements. In Fig. 13(a),
 367 the power losses at each stage are shown based on the
 368 analytical coil efficiency calculations, and based on the SPICE-
 369 simulated rectifier circuit; the PA efficiency was based on
 370 the vendor-measured values from the datasheet. Fig. 13(b)
 371 shows the breakdown of the measured losses for the direct
 372 link used to evaluate the system's power handling and end-
 373 to-end efficiency. The coil reflection was estimated based on
 374 the full-wave simulated and measured small-signal S_{11} of the
 375 coils, around -20 dB.

376 Both the end-to-end efficiency and the rectifier's RF-DC
 377 efficiency were characterised for varying loads at different
 378 power levels, and are shown in Fig. 14(a) and (b), respectively.
 379 From the measured efficiency response, it can be seen that
 380 the load can be varied across a 7:1 resistance ratio, enabling
 381 high-current loads to be powered. The observed fluctuations
 382 in Fig. 15(b) are attributed to minor fluctuations in the coils'
 383 separation, which are more noticeable at shorter ranges.

384 Given the system's wearable application, minimising spuri-
 385 ous emissions is essential. The electromagnetic fields around
 386 the receiving coil and its integrated rectifier were measured
 387 using a near-field probe (Rohde and Schwarz RS.H 400-1),
 388 connected to the oscilloscope. The Fast Fourier Transform
 389 (FFT) is shown in Fig. 15. The fields were measured around
 390 the coil's turns, away from the rectifier, and directly above the

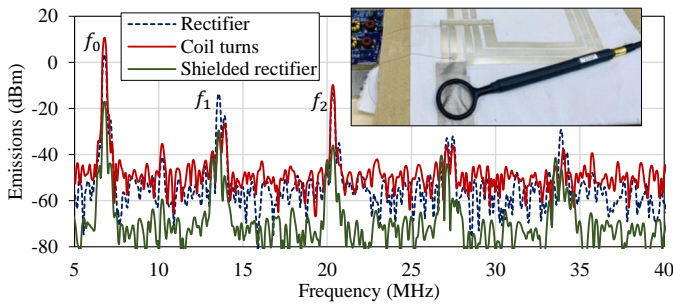


Fig. 15. Measured frequency-domain response of the receiving coil showing the fundamental (6.78 MHz) tone and its harmonics; the inset shows the measurement setup of the shielded rectifier

391 diodes. Due to their non-linearity, the rectifying diodes are
 392 expected to generate additional harmonics. From Fig. 15, it
 393 can be seen that the second and third harmonics are around
 394 -11 dBm over the rectifier. To demonstrate the feasibility of
 395 shielding the proposed rectifier, a layer of conductive fabric
 396 was attached to the encapsulating PU layer. As observed in
 397 Fig. 15, the additional shielding layer reduces the first- and
 398 second-order harmonics by up to 17 dB, to under -20 dBm.
 399 Additional magnetic shielding could also be used based on
 400 flexible ferrite films.

401 **C. Wireless-Powered Heater System Evaluation**

402 A key example of thermal e-textiles are long-term ther-
 403 apeutics and recovery [15], [38], where a temperature up
 404 to 60°C could be required. The performance of the WPT
 405 system if further evaluated in conjunction with the load, the
 406 resistive printed heater. To realize the heater on the same fabric
 407 substrate, a 65%/35% carbon/silver paste was prepared and
 408 screen-printed onto a PU film which is then laminated on the
 409 same textile material alongside the coils. The carbon/silver
 410 formula was optimized to achieve a resistance as close as
 411 possible to the optimum load of the rectifier. The heater is
 412 formed of a meandered trace with 18 folds and is 9×9 cm.
 413 The cured and laminated heater had a measured low-voltage
 414 resistance of 270Ω at room temperature. Fig. 16(a) shows the
 415 experimental setup used in evaluating the wireless-powered
 416 heater.

417 Prior to testing the integrated system, the heater was con-
 418 nected directly to a bench DC power supply to evaluate its
 419 power requirements. The IR camera was used to observe the
 420 thermal distribution over the heater and a thermocouple was
 421 placed where the highest temperatures were observed to cross-
 422 validate the IR measurements. Fig. 17 shows the heater's
 423 temperature change and absolute peak temperate as a function
 424 of its DC input up to 30 V. In most wearable rehabilitation and
 425 treatment applications, temperatures exceeding 60°C are not
 426 typically required [39]. Therefore, the maximum DC power
 427 consumption of the heater can be estimated to be 3 W.

428 The heater was subsequently connected to the rectifier's
 429 output, as in Fig. 16(a), and a DC input power sweep was per-
 430 formed at two different separations between the transmitting
 431 and receiving textile coils. Low resistance conductive copper
 432 threads were used to connect the rectifier's DC output to the

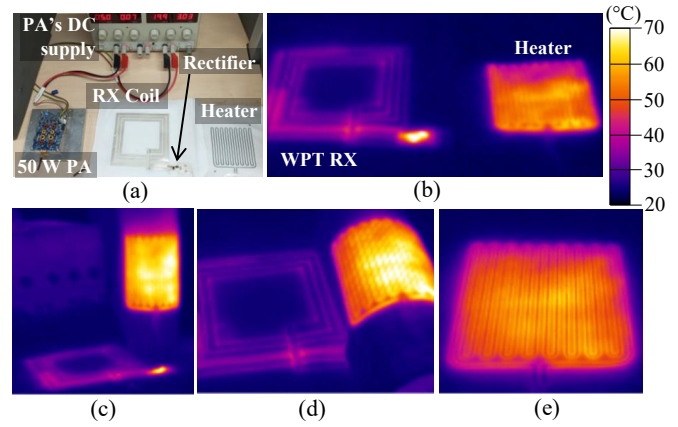


Fig. 16. The wireless-powered heater: (a) measurement setup the transmitting coil is placed beneath the identical receiver and connected to the PA with a low-loss coaxial cable); (b) IR image under flat conditions (<0.5 cm coil separation); (c, d) the functional heater under bending; (e) the heater powered with a 2 cm gap between the coils with a 3 W DC received power.

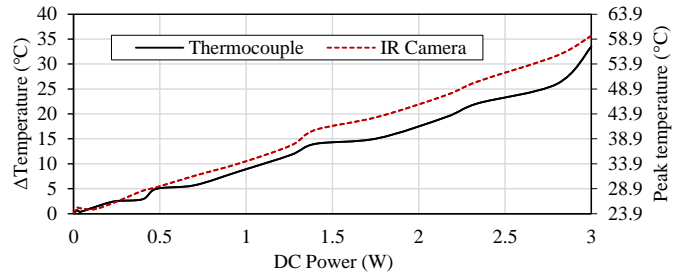


Fig. 17. Peak temperature of the screen-printed carbon/silver heater using a bench power supply.

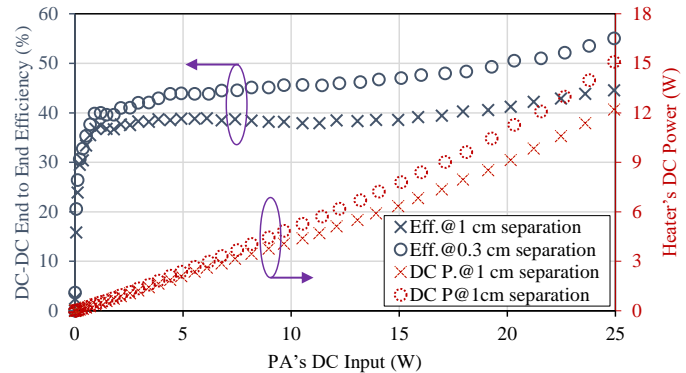


Fig. 18. The end-to-end efficiency and received power using the heater as a load for varying input power levels at different separations.

433 heater to demonstrate that the heater could be placed on a
 434 different body part to that hosting the coil. Fig. 18 shows the
 435 measured DC power delivered to the heater and the calculated
 436 end-to-end efficiency of the WPT system as it powers the load.
 437 The temperature of the wearable heater when driven at 15 W
 438 is shown in the IR photographs in Fig. 16(b) to (d), including
 439 when the heater is bent.

440 It can be observed in Fig. 18 that the peak end-to-end
 441 efficiency approaches that observed with the dummy resistive
 442 load. Moreover, a peak DC power output of 15 W could be

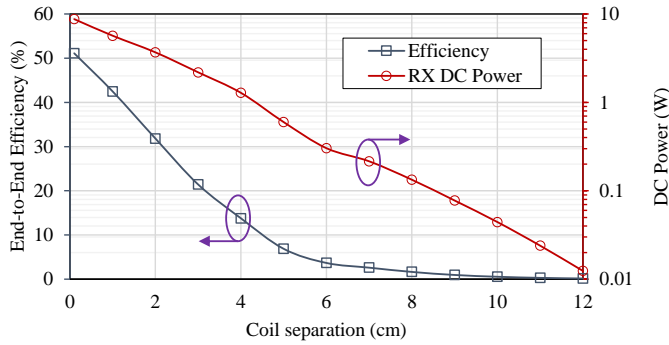


Fig. 19. Characterization of the DC power delivery to the heater over varying separation from the transmitter.

delivered to the heating element. Given the maximum power consumption of 3 W for a peak temperature of 59°C to be reached by the heater, in Fig. 18, the received DC power is sufficient for powering multiple heating elements on different body parts. The control circuitry could also be powered within the available energy budget and a wearable energy storage device could also be charged [9].

Following the validation of the WPT-powered heating system and identifying 3 W as the peak power consumption of the individual heater, the system was characterized for varying coil separations. Fig. 19 shows the measured DC power output as a function of the distance between the textile-based transmitter and receiver. At 2 cm separation, the DC power output is just over 3 W which can supply the heater with an end-to-end efficiency around 30%; this efficiency is comparable to that of a Qi-standard WPT system which can only deliver 1.2 W with minimal coil separation and using rigid power conversion circuitry of higher complexity [24]. The observed drop in the efficiency for varying separation is attributed to the impedance mismatch at the PA's output. This can be mitigated through the use of an adaptive matching network [40] on the transmitter, which does not need to be flexible or textile-based. The transmitter coil could also be driven at a constant current to achieve load-independent operation [41].

In Fig. 16(e), the temperature across the surface of the heater with the 2 cm coil separation results in a peak temperature exceeding 60°C. At higher separation distances, the power output drops to mW levels which can only be used to power smaller sensors and wearable devices. Beyond 12 cm, the DC power output is comparable to that of radiative far-field WPT systems implying that a dual-mode near/far-field implementation could be utilized [18], [25].

The final step in characterizing the WPT system is evaluating its safety for use in a standard unregulated setting. The Specific Absorption Rate (SAR) was simulated over a homogeneous skin phantom placed with 1 mm separation from the receiving coil. The SAR was calculated in CST Microwave Studio and averaged over 10 and 1 g tissue mass. Fig. 20 shows the simulated SAR distribution, calculated for a 25 W input at the on-body receiving coil. With a peak SAR of 0.247 W/kg for a 25 W received RF power level, it can be seen that the coils operate well below the 1.6 W/kg SAR limit of the IEEE C95.1 standard. Therefore, the main limiting factor for

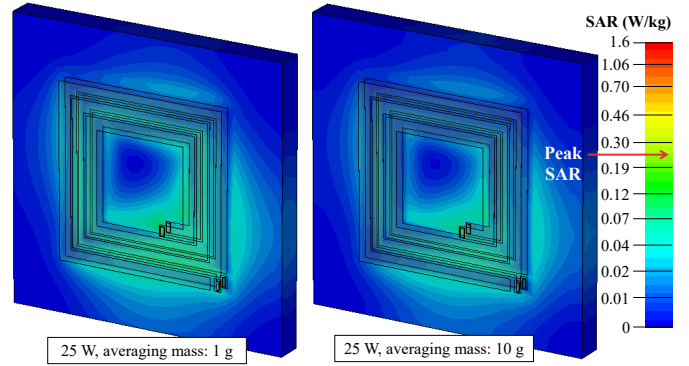


Fig. 20. Simulated SAR distribution for 25 W of 6.78 MHz power at the receiving (on-body) coil.

TABLE II
COMPARISON WITH RECENT WEARABLE WIRELESS POWER RECEIVERS

Work and WPT mode	DC Power	Peak Efficiency	Resonator/antenna material	Rectifier materials
This work: IPT	1–15 W with >50% DC-DC efficiency	DC-DC: 60%; RF-DC: 90%	Printed silver on textile	Printed silver with SiC diodes
[24]: Qi IPT	1.51 W with <37% DC-DC efficiency	DC-DC: 37%; RF-DC: NR	Screen-printed coil	COTS Qi rectifier
[25]: 6.78 MHz resonant IPT	1–3.5 W with <32% DC-DC efficiency	DC-DC: 32%; RF-DC: ≈45%	Embroidered e-thread	Discrete capacitor with Si diodes
[17]: E/H mid-field coupling	1–200 mW	DC-DC: <5%; RF-DC: 50–80%	Embroidered e-thread	Discrete matching with Si diodes
[9]: far-field radiation	0.1–20 mW	DC-DC: <0.1%; RF-DC: 50–80%	Flexible circuit filament in textile	Discrete matching and diodes on a flex filament

NR: not reported, off-the-shelf rectifier

the power level at which the coils can be driven at will be the heat dissipation of both the coils and rectifier, which could cause discomfort to the user.

Despite the extensive literature on electromagnetic near-field links for wearable WPT, there are limited works which have demonstrated a full system including the power conversion circuitry and a load. Table II compares this work to state-of-the-art wearable WPT receivers from the near-field to far-field. From Table II, it can be seen that the proposed system represents over a five-fold improvement in the DC power output over previous flexible WPT implementations and at least 100% DC-DC efficiency improvement, while being the first to use an all-flexible receiver. Moreover, the all-flexible screen-printed fabrication process enables the system to be scaled for most large-area industrial electronic applications. Finally, this work is the first to demonstrate a high-power wearable application, a textile-based Joule heater, being wirelessly-powered using COTS semiconductors and printed textile-based passives with a high DC-DC efficiency approaching that of a dummy load.

V. CONCLUSION

This paper presented an all-flexible printable WPT system and demonstrated it powering a textile-based Joule heater on the same substrate. The designed voltage doubler maintains an RF-DC efficiency over 80% for >1 W inputs, and a peak efficiency over 90% up to 40 W. The integrated system demonstrated a DC-DC efficiency approaching 60% with a 14 W DC output, enabling the textile-based heater to be powered at 2 cm away from the transmitter. The proposed system overcomes the limitations of existing flexible and wearable WPT systems based on:

- 1) High power handling: achieved through embedding a large-area low-loss tuning capacitor within the coil for improved thermal dissipation.
- 2) Reduced thermal losses: achieved through the use of low-loss diodes, reducing the temperature rise by nearly three-fold over previous flexible rectifiers.
- 3) Improved application-specific end-to-end efficiency, achieved by designing the load (the heating element) to approach the optimum current draw of the rectifier for improved RF-DC conversion.
- 4) Improved reliability and printability: by limiting the use of discrete rigid components to the SiC diodes as well as fabricating and encapsulating all passives using the same screen-printing process.

This work shows for the first time that flexible e-textile WPT systems can deliver Watt-level outputs efficiently. The printed heater demonstrated evidences that high-power wearable applications could become battery-free using WPT.

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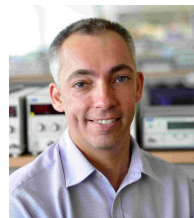


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