New Materials for RF and Microwave Technologies Workshop

3 - 4 December 2014

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Motivation for the workshop

EPSRC identified RF and Microwave Devices (http://www.epsrc.ac.uk/research/ourportfolio/researchareas/rfmicrodev/) as an area for growth over the current delivery plan and highlighted opportunities for researchers in the area to work with materials scientists. The Information and Communication Technologies (ICT) Theme wished to engage with the researchers across RF and microwave technologies and materials science to identify the technical challenges which could be addressed by existing materials or the co-design of new materials to meet the needs of RF and microwave technologies. The aim was to build a picture of the research challenges relating to RF and microwave technologies where existing or new materials could produce a step change in performance or ability and identify materials that could enable these changes.

Objectives of the workshop

The objectives of the workshop were to:

- Identify specific research challenges in RF and Microwave Devices in which new materials might lead to a step change in technology or performance. Addressing such challenges would necessitate collaboration between RF and microwave technologies and materials researchers.

- Identify classes of materials that have properties which offer potential for a step change in RF and microwave technologies and link these to the research challenges identified.

- Create a timeline or roadmap for materials exploration and RF and microwave technology development.

- Initiate future research collaborations and engagement by introducing researchers from the various communities in a neutral environment.

- Identify potential future actions which may facilitate collaboration between the RF and microwave technologies and materials communities.

Delegate selection

An open call was issued on the EPSRC website inviting expressions of interest to attend the workshop. Over 70 applications were received from which 42 delegates were invited to attend the event on 3 and 4 December 2014 in Birmingham. The
selection of delegates was made by the ICT Theme based on the application form ensuring a breadth of expertise, institutional representation, career stages and academic/industry background of delegates. A full list of delegates is given in Appendix 1 of this report.

**Agenda**
The workshop was held on 3 to 4 December at the Hilton Birmingham Metropole, Birmingham NEC. The agenda was as follows:

**Day 1**

1400  Welcome  
*Liam Blackwell, EPSRC ICT Theme Lead*

“Antennas from new emerging materials”  
*Yang Hao, Queen Mary University of London*

“New structures for new devices”  
*Neil Alford, Imperial College*

“Challenges for high frequency materials characterisation”  
*Adrian Porch, Cardiff University*

“Microwave ceramics for resonators, filters and antennas”  
*Ian Reaney, University of Sheffield*

“Defence research drivers for advanced RF and microwave materials”  
*Ian Youngs, Dstl*

Reflection Session

Wrap up and close

1700  End of day one

**Day 2**

0930  Introduction to day two
Exploring the research challenges in RF and microwave technologies where new materials might lead to a step change

What are the required properties of materials to lead to a step change in RF and microwave technologies?

1210 Lunch

1300 *In parallel* clustering and prioritisation of:
- RF and microwave challenges
- Classes of materials which have potential to meet property requirements

Links between RF and microwave challenges and classes of materials

Future actions which may facilitate future collaboration

Wrap up and close

1600 End of workshop

Workshop outputs

1. Setting the scene

The workshop began with a number of talks from members of the community to set the scene for the rest of the event. At the end of the talks delegates were asked to reflect on what had been discussed and share their thoughts on the area of materials in RF and microwave technologies. The following points were noted¹:

- Active semi-conductor electronic materials and devices
  - Do not forget III–V electronic devices. These are new developments in RF and microwave technologies.
  - III–V materials (InP, GaN) re-engineered for RF and microwave technologies
  - Development of tuneable band filters with low insertion loss and high rejection to enable development of software and cognitive radio
  - Active materials for microwaves to enhance device integration, power efficiency, and high frequencies operation. This will include antenna system integration.
  - Active devices/materials are emerging as an important RF Technology

¹ The points noted at the workshop have subsequently been clustered to highlight some common themes.
– New materials/novel approaches for active devices/architectures (transistors, diodes)
– “Out of the box thinking” to utilise emerging/smart materials such as graphene, which do not have great conductivity, but are tuneable and have high mobility, flexibility for potential sensing, plasmonics applications
– Organic materials for RF/Microwave electronics including spintronics
– High power vacuum electronics. Networks of teams required to solve challenges in THz region
– High power, high frequency amplifiers and oscillators in the 0.1 to 1 THz range will be important for realising future applications

• Extended and smart material properties (size, weight and power)
  – Techniques of utilising advanced materials to meet the “theoretical limits” and beyond
  – Novel materials to enable a step change at high frequencies?
  – Light-weight materials
  – Device miniaturisation techniques and materials at low frequency (current R&D seems to be looking higher frequencies)
  – New physics such as “OAM” (Orbital Angular Momentum) for innovative antennas and communications
  – Develop smart – tuneable property materials
  – Control the anisotropy in materials – understand the system/application benefits
  – Overlap of materials with THz applications will be important for the future, high energy transmission lines with glass – metal – dielectric that is vacuum compatible
  – Materials to isolate antenna elements in confined space, volume
  – New materials for antennas in RF/Microwave energy harvesting

• Design and fabrication
  – Develop manufacturing techniques for polymer/conducting hybrids
  – Explore printable magnetic materials at high frequencies
  – Techniques for synthesis of material microstructures to control macroscopic properties

• System perspective and integration
  – Create new measurement techniques for advanced materials, antennas and devices
  – Understanding new material requirements for antennas and RF/Microwave devices
  – Ways to enable the operation of multiple frequencies into a single antenna
• “System thinking?” – from the RF/Microwave frontend to signal manipulation and data storage
  - Class of materials: different according to which part of the “system” (noting need to trade performance/cost according to application)
  - RF/Microwave packaging → another crucial part of supply chain
  - Integrated beam forming antenna with RF/Microwave front ends
  - High-power RF/Microwave applications including medical applications
  - Need to understand and develop sub-systems and components in the context of end-to-end performance specification using simulation and testing
  - Dual functionality of microwave structures

• Vision and strategy
  - Status of supply chain for ITAR–free access to RF devices, 5G communication technologies
  - Identify most “disruptive” technology scheduled for 2020
  - In RF and microwave technologies the UK has backed defence rather than the consumer market, this has had consequences
  - Ability to prioritise investment in face of many materials, many devices/sub-systems concepts, and many potential market opportunities
  - Need a vision in terms of national outcomes to lead community forward through a focused set of technological and application challenges
  - Balance between shorter-term targeted research to unlock economic growth versus longer term strategic opportunities for sustainable advantage (2 roles)
  - May be difficult for the UK to compete in mass markets such as mobile communications hardware
  - UK RF and microwave research should not try to compete with mature global industry aimed for consumer electronics but must identify completely new technology with patent protection
  - Synergy and priorities of science and technology across and between sectors (defence and security in partnership with civil sectors)
  - As a community we have real strengths in antenna research – we really look for disruptive technologies

• Investment approach
  - “Working together” between material experts and antenna engineers for advanced materials including metamaterials
  - Targeted funding opportunity for this community working with materials
  - Review roles of professional bodies for the community
  - Understand role of public sector investment

7
2. Exploring the research challenges in RF and microwave technologies where new materials might lead to a step change

The objective of this session was to discuss the research challenges in RF and microwave technologies where materials might lead to a step change in technology or performance. Delegates were selected so that there was a range of expertise in each group, these groups were mixed part way through the session to facilitate further discussion.

Later in the day the delegates were asked to group the challenges into clusters, this resulted in nine high level research challenges being identified. Delegates were then asked to prioritise these challenges by voting. In priority order (highest to lowest) the research challenges identified were:

| R7 – Active materials and devices (15 votes) | • Active devices for sub 6GHz and mm wave linear and power efficient LNAs, PAs and mixers  
• Power – user– heat generation  
• Weight  
• Size  
• Dynamic power control on chip  
• RF and Microwave GaN  
• High frequency GaN devices >6GHz, linear and reliable  
• Material – characterisation – modelling  
• Add value to current platform technology – CMOS  
• Active and passive  
• PZ on antenna design – organic structures  
• Multi-layer structures and or/material  
• RF sources, mixers, LNAs, PAs  
• Smart materials that breakdown and recover under electric field, light, ultrasound, pressure, chemical attack  
• E-field generators – structures  
• Integration of GaN (III–V) on Si, power and RF capability  
• RTDs (resonant tunnelling diodes)  
• Local RF III-V fab industry required  
• Active materials  
• Active devices for frequencies >6GHz (... 30GHz) (e.g. GaN and diamond)  
• Ultra low noise amplifiers < 1K noise temp  
• Ultra low power |
| R4 – Agility (frequency) | • Dispersion engineered material: arbitrary phase shift; $\varepsilon_r$, $\mu$, $\sigma$ |
| **adjustment, one system for many different bands)**  
<table>
<thead>
<tr>
<th><strong>(8 votes)</strong></th>
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<tbody>
<tr>
<td>• Tuneable low loss dielectrics</td>
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<tr>
<td>• Tuneable filters - can we change resonator shape?</td>
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<tr>
<td>• Optically controlled materials</td>
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<td>• Reconfigurable materials</td>
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<tr>
<td>• Multi-layered materials broken into flakes or “onion skin” materials – core shell nanoparticles</td>
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<td>• Self-actuating materials (morphing)</td>
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<tr>
<td>• Antenna elements and beam formers for 30GHz → 300GHz</td>
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<tr>
<td>• Tailored materials – dispersion engineered</td>
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<tr>
<td>• Tunable materials</td>
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<tr>
<td>• Tunable notches (multiple notches) for filtennas</td>
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<tr>
<td>• Tunable absorbers from materials synthesis, microwave absorbing coatings, etc.</td>
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<tr>
<td>• Tunability and reconfigurability</td>
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<td>• Tunable microwaves for directed synthesis/ activated chemical processes</td>
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<tr>
<td>• Active materials – tunable, integrated amplifiers</td>
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<td>• Multi-functional materials / multi-domains</td>
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<tr>
<td>• Multiferroics</td>
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<tr>
<td>• Designed porous materials decorated with metals for tunable microwave properties – core-shell nanoparticles</td>
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<td>• Loss-less tunable materials</td>
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<tr>
<td>• Tunable integrated RF front ends</td>
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<tr>
<td>• Materials which are switchable between RF transparency and conductive</td>
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<tr>
<td>• Need broadband materials (or tunable), maybe call for “frequency agile materials”</td>
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<tr>
<td>• Tunable antennas/ filters from &lt;6GHz transceivers</td>
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<td>• Improved bandwidth</td>
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| **R1 – Terahertz (< 2THz, room temperature)**  
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<tr>
<td>• Chips – limits</td>
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<tr>
<td>• Making microwave sources a commodity</td>
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<tr>
<td>• Technology enablers for X 1000 capacity for future communications</td>
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<tr>
<td>• Manufacturing of THz wave guides and components</td>
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<tr>
<td>• Medical imaging</td>
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<tr>
<td>• Manufacturing of small sizes for THz</td>
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<tr>
<td>• Very high frequency characterisation</td>
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<tr>
<td>• Mobile network infrastructure trend to pico-cells</td>
</tr>
<tr>
<td>• Interconnects – new ideas</td>
</tr>
<tr>
<td>• Broadband in THz for material characterisation</td>
</tr>
</tbody>
</table>
- THz: need to develop room temperature, compact, >100 milliwatt continuous wave sources: detectors already at quantum limit
- THz for wireless limits between chips for machine to machine communications
- Crossover between metals and plasmonics for THz
- Microwave (6-18GHz) active devices
- THz: sources; detectors
- Reliability → persistent use → works when needed (short term) (long term)
- Antennas >100GHz? Miniaturisation not so much an issue – different rules / concepts apply?
- Integration
- Chip packing
- THz challenges difficult
- THz has big potential but big challenges to get to a useful TRL
- THz devices (higher power) and antennas for space applications and airport sensing

| R3 – Antennas | • Operation at multiple bands over narrow channels
| (5 votes)     | • Overcome the Chu’s limit? – particularly for intermediate and low frequency antennas
|              | • Transparent antennas
|              | • Circulators are not wide band, ferrites are heavy (needed on front ends)
|              | • Control dispersion in antenna materials → through materials technology
|              | • Doped graphene, transparent for antennas
|              | • Thin conformal antennas
|              | • RF “LED” – integrated system of antennas + frontend in single package |

| R9 – Power (High power up to kWs) | • High power, high bandwidth, small size
| (5 votes)                           | • Materials for >1kW solid state sources
|                                    | • Power for fast measurements
|                                    | • Optical to microwave conversion
|                                    | • Front-end (“system” not only components)
|                                    | • Efficient (too much power consumption now)
|                                    | • Understanding material characterisation (>0.3THz)
|                                    | • Efficiency
|                                    | • Losses – Efficiency |
- High power handling
- Discussion was not focussed
  1) what part of the spectrum to focus on
  2) whether it is Si-scaling being cost effective
  3) Resurrection of III–V industry
  4) Challenges of micromachines
  5) THz sources alignment of wave guide challenges
- Thermal management: efficiency in systems; non-linearity?
- Microwave sources – high power at high frequency?
- Wireless power (no cables)
- Wireless power – at distance
- Source of energy
- Losses very important
- Power amplifiers on antennas
- High power materials

| R2- System design and manufacture (3 votes) | • Integration of active devices (i.e. transistors) with antennas working above 100GHz  
• Integrating antennas with sensors  
• Research challenges in RF and MW  
  - applications of MW for development of high quality engineering – ceramics  
  - chemical synthesis (organic) to-date only crude process feedback control of MW material’s processing  
  Added Quality – near theoretical density sintering → enhanced  
• Cost  
• Systems approach – co-design of whole system from front end RF to baseband  
• System on a chip including antennas: alternative substrates e.g. 2D materials?  
• Rapid-printable conductors on thermally sensitive substrates  
• System co-design  
• Low-loss, low $\varepsilon_r$ (permittivity) to enable mm-wave system integration. Need good manufacturing, tolerance, metal deposition, vias  
• Smaller – more integrated systems – lower loss  
• Highly integrated wireless sensing – lab-on-an-antenna? |
| **R6 – Low loss materials and applications**  
| (1 vote) | • Very low frequency characterisation  
| | • Chemical synthesis (with RF)  
| | • "Thin" i.e. 3µm films  
| | • Efficient components for millimetre wave connectivity  
| | • Higher permeability, lower loss ferrites at microwave  
| | • Higher Purcell factor resonators  
| | • Small low frequency as important as moving to high frequency  
| | • Low loss / high loss materials  
| | • Cost of materials  
| | • High Q-factor – small size – common  
| | • Directed synthesis tunable source  
| | • Medical and other applications |
| **R8 – Soft/flexible substrates**  
| (1 vote) | • On body – modular – reconfigurable based on dynamics local EM environment and posture  
| | • High permittivity for fabrics for wearable antennas  
| | • Wearables  
| | • Alternative/new substrate types  
| | • Biodegradable  
| | • Flexible conductors  
| | • Exploit magnetics .... on chips? e.g. isolators  
| | • manufacture cost/ scale  
| | • Flexible connectors for wearable antennas  
| | • High conductivity materials e.g. fabric, rapid prototype  
| | • Interconnects  
| | • Microwave capable textiles  
| | • Reduce cost for electronic integration fab -“cottage industry in IC fab”  
| | • Effects of anisotropy  
| | • Disposable distributed sensing → single point change in function sense → transmit (smart materials/ systems)  
| | • Materials (novel) interactions with virtual – photon fields – Lienard Wiechert potential interactions |
| **R5- Community (Networking)**  
| (0 votes) | • THz – bridge the gap  between physics and engineering  
| | • Where is the broader UK community meeting?  
| | • Force collaboration – too many chiefs in RF  
| | • How do we get a UK industry in RF – where are UK drivers for business?  
| | • More interaction needed between physics and fundamental studies and “real world” engineers |
• Potential of 2D materials tested in labs, requires more testing by engineers
• No RF / microwave community meeting
• Mobile industry?
• Defence/specialised apps – getting devices
• THz challenges?
• Why are there no industrial people?
• Need a UK RF/ microwave/ THz community meeting every year

### 3. What are the required properties of materials to lead to a step change in RF and microwave technologies?

The aim of this session was to consider properties of materials required to lead to a step change in technology or performance of RF and microwave devices. Delegates were selected so that there was a range of expertise in each group, these groups were mixed part way through the session to facilitate further discussion.

Later in the day the delegates were asked to group the properties into clusters, this resulted in 11 different groups of desirable characteristics being identified. Delegates were then asked to prioritise these properties by voting. In priority order (highest to lowest) the identified were:

| M10 – Tunability (11 votes) | Higher $\varepsilon_r$ with tenability  
Microwave induced drug release droplets and explode  
Active materials (change $\varepsilon$ and $\mu$)  
Low energy switching  
Liquid crystals: losses > 20GHz? versus switching speeds?  
Tunable materials – variable $\varepsilon$ and $\mu$  
Low volts / power ~ 5V and < $\mu$W consumption  
Multifunctional materials (structural, $\varepsilon$ and $\mu$, RF power in one object)  
Engineered materials from multi-ferroics  
Transparent and switchable tunable band gap and /or density of states – low loss  
30GHz < $f$ < 100GHz, $\varepsilon$ > 100 and tunable  
High voltage “fine”, low current “must” for tunable materials |
| M8 – Magnetic Materials (ferromagnetics, diamagnetic, ferrites, paramagnetic, anti-magnetic) (9 votes) | • Fundamental limit of EM functional materials  
• Wide bandwidth materials (40 – 50% )  
• Conventional dielectrics  
• Non-ferrite magnetic materials  
• Low loss integrated magnetics at 10GHz or higher - multi-ferroics  
• Magnetic materials in RF |
| M6 – Composites (5 votes) | • Artificial dielectrics  
• Metamaterials  
• Composites multi-layers and hybrid materials  
• Functional materials  
• Controlled grading in materials  
• Nanomaterials  
• Gradient index materials  
• Gradient materials: z – variation, x-y lateral dimensions  
• RF composites $1 < \varepsilon_r < 30$, $1 < \mu_r < 1000$  
• RF composites and synergistic materials – allow incorporation of RF function in novel structures and material systems  
• Graded permittivity i.e. control of $\varepsilon_r$ with location  
• Functionality graded materials as a step to fully |
transformative materials
- High quality (low loss) textile materials
- Microscopically graded material characterisation – non – destructively

| M1 – Actives (4 votes) | • Multi-function transmit (high power receiver)
• GaN is a step change, UK not engaged – what beyond GaN?
• Active materials
• Multifunction. Transmit (high power) receiver
• Old materials in new light “GaN on diamond”
• New materials → New challenges but new opportunities (e.g. 2D materials); new approaches required – need to think out of the box →e.g. plasmonics, transparency, stretchable, tunablility, etc.,
• Higher speed <nS
• Higher extinction ration 20dB; 2D graphene – related
• 2D materials other than graphene |

| M9 – Manufacturability (2 votes) | • Depositable semiconductor, diamond?
• Membrane technology
• Fabrication – woven antenna in a multi-layer structure → reduced “length”
• Epitaxial
• Scalability
• Depositable semiconductor, μ > 10Kcm²
• Conductive / dielectric mix rapid prototype materials
• Conventional CNC
• Size smaller (low frequency) larger (high frequency)
• Bio-construction
• Scale down to 10μm max dimension to 20cm (for GHz →THz devices) passives
• Bio-materials: bio-degradable, bio-compatible, self heal
• Environmentally friendly
• Cheap!
• Service – life
• Injection moulding of high volume microwave circuits
• Cheap, organic, semi-conducting polymers (for incorporation into antenna front-ends)
• ”Ideal” real-time tunability and low losses
• Manufacture : <1μm resolution, ~ cm area fast, 3D
• Controllable dispersion in spectral and spatial domain |
- Microwave electro-acoustic materials
- Diamond for thermal control of actives: increase heat conductivity, decrease electrical conductivity
- Materials with $\sigma > 10^7 \text{S/m}$ (high conductivity 3D printable compatible with any platform)
- Development of methods to exploit new materials – graphene and GaN
- “digital metamaterials” tailor-made $\varepsilon_r$ structures
- Metallisation in curved 3D geometrics
- Aim: reduce investment costs to set up mass production by factor of 10 “universal manufacturing”
- Packing materials – substrate, conductors, packages

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<thead>
<tr>
<th><strong>M5 – Printing</strong> (2 votes)</th>
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<tbody>
<tr>
<td>- Ability to print metal and non-metal in 3D shapes</td>
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<tr>
<td>- Anisotropic materials multi-layer thin film conductors, ferromagnetic dielectrics</td>
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<tr>
<td>- Metallisation in 3D – discretely, quality of film electrically</td>
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<tr>
<td>- 3D printing for RF systems</td>
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<tr>
<td>- Miniature 3D printing ~10-50µm over large areas 5cm</td>
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<tr>
<td>- 3D – printable, low-loss ($\tan &lt; 0.0001$) – engineering ceramics</td>
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<tr>
<td>- Fabrication with incompatible materials e.g. melt temp etc.</td>
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<tr>
<td>- 3D printing vs. 2D printing</td>
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<tr>
<td>- Uniform build rates for mixed dielectric, conductors, magnetic materials in 3D or in 2D (matched stresses)</td>
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<tr>
<td>- Print conductors and dielectrics in 3D geometry</td>
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<tr>
<td>- Increase permeability</td>
</tr>
<tr>
<td>- Combinations of application constraints and max RF microwave performance</td>
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<tr>
<td>- Mechanical, thermal, dielectric properties. Chemistry applications: regio-chemistry</td>
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<table>
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<tr>
<th><strong>M11 - Absorbers</strong> (1 vote)</th>
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<tr>
<td>- Conducting polymers – material lifetime</td>
</tr>
<tr>
<td>- $0 \leq \varepsilon \leq \infty$, $\varepsilon = \mu$ from DC – THz, 2D → bulk, lossless + high loss</td>
</tr>
<tr>
<td>- High loss: absorbers, loads, bio materials (tissue)</td>
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<tr>
<td>- &gt; 100 MHz, polymers – insulating but very processible smooth $\varepsilon &gt; 3$</td>
</tr>
<tr>
<td>- High loss materials (high $\varepsilon''$ and $\mu''$)</td>
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<tr>
<td>- Balanced materials ($\varepsilon = \mu$)</td>
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</table>
| M4 – CAD Modelling (thermodynamics coupled with e/m) (1 vote) | • CAD – RF with new materials – specification to end design CAD  
• Intelligent RF and microwave CAD  
• RF modelling in house expertise combined with commercial software  
• Models of new materials  
• Material processing applications – drying – moisture sensing  
• Multi-physics / multi-scale to system level  
• Internet of things (integration into anything) |
| M2 -THz (0 votes) | • Intelligence led high throughput screening of particle¹ / particle² composites  
• Cheap, inorganic near-100% transparent THz (1-10THz) windows  
• 300GHz materials  
• µr above 10 GHz while µi is held low (relative permeability is µ = µ_r + jµ_i)  
• Ultrafast switches / modulators for 300GHz more activity needed  
• Switching vs. modulation different applications  
• Medical therapy (adaptive power) |
| M3 – Engineering Mechanical (0 votes) | • 1GHz → mm wave  
• Toughness and losses, quality of fab  
• Polymers ε≥3  
• Fundamental limits ε=µ  
• Active materials – large charge < 6GHz mm wave, ε, µ, morphy  
• 3D build: uniform build rates characterisation stressed  
• Light weighing space – high power  
• Roughness → adds loss (wavelength dependence)  
• Smoothness → adhesion issue?  
• Quality of contact metal/ ceramics/ polymers  
• Managed thermal properties  
• Lightweight / low-density broadband  
• Mechanical requirements  
• Cheap materials with high permittivity εr > 10  
• Dielectric with thermal management of metal  
• Vacuum compatible  
• Mechanical + temperature + vacuum  
• Environmentally stable |
- Substrate roughness reduction through use of new materials (substrate-metal interface in antennas)
- Flexible ceramics
- Transparent materials (RF + microwave also visible)
- Flexible ferroelectric polymers
- Anisotropic materials are desirable for wearables
- Biodegradable materials

<table>
<thead>
<tr>
<th>M7 – Low-Loss Antennas (0 votes)</th>
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<tbody>
<tr>
<td>Low-loss materials (can handle less than a few volts)</td>
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<tr>
<td>Low-loss and high-loss materials</td>
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<tr>
<td>High power &gt;10s KW – microwave</td>
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<tr>
<td>Low-loss wire/feed lines for antenna feeds, beam formers</td>
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<tr>
<td>Relative permeability $\mu_r &gt; 1$, low loss, $&gt;1$ GHz</td>
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<tr>
<td>Low-loss: $\tan \Delta &lt;&lt; 10^{-9}$</td>
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<tr>
<td>Antennas $\rightarrow$ system $\rightarrow$ array; interconnects; conductors; devices technology</td>
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<tr>
<td>Multi antenna meta materials dielectrics magnetics</td>
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<tr>
<td>Beam forming – novel phase change: morphing; solid state electronics; smart materials</td>
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4. Links between RF and microwave challenges and properties of materials

Having identified and prioritised the research challenges in RF and microwave technologies and the desired properties of materials which might contribute to addressing these, the delegates were asked to consider the links between them (Figure 1).
Figure 1: Links between research challenges in RF and microwave technologies and materials-based groups which might contribute to addressing these. The thickness of the line relates to the number of times a link was identified.
5. Future actions which may facilitate future collaboration

In groups, the delegates discussed what actions by the community (including users) and funders might facilitate collaboration to develop materials with the desired properties to address the identified research challenges in RF and microwave technologies. They also considered who else, for example researchers from other disciplines, might need to be involved in addressing these challenges.

Actions for the community (including users):

- Strengthen links between materials and design communities
- RF community to communicate their needs
- Keep communicating e.g. networks, annual meetings
  - To generate new ideas
  - Discuss what has happened
  - Discuss whether priorities have changed
  - Discuss new priorities
  - Target discussions on particular interface / application domain
  - Include more industrialists / SMEs
- Network for this community – people need to and want to connect
- Exposing industry to the research going on in universities
- Infrastructure people
- Communication
- Increase awareness amongst community – who is doing what
- Awareness of international research activities
- Workshops, for example a joint CommNet 2 and Teranet workshop, involve current PhDs in the fields – RF communications and materials
- Postgraduate conference
- Summer schools
- IET seminar on this area
- IEEE – invited distinguished speakers
- Apply for funding
- Industry – BAE Systems, Selex, Thales
- An ‘organic evolving’ project (collaborative) (e.g. ESA) involving an agency to tap into (SSTL, Satellite Applications Catapult)
- Role for CDT’s:
  - Students that cross-fertilise interactions (mechanism that brings together groups)
  - Weighting metric for CDTs to enable this
  - Student as a ‘vector’ to facilitate this
- Role for universities to cross-fertilise departments
- Communication/coordination with universities (without cohesion)
• My Community forum
• IET – 2015 5G WS – can we include this in topics?
• IoM
• Institute of Physics Dielectrics Group
• Cross-discipline working e.g. PDRA exchange
• Link proposals to EPSRC’s strategy and remember this in peer review

**Actions for funders:**

• Promote collaborative projects across disciplines
• More joint funding/collaboration this will provide new directions
• Events
• Positively influencing
• Inter-disciplinary call for proposals e.g. Bridging the Gaps call with materials science
• Staged proposals to increase TRL in materials and then in RF
• Network funding, for example CommNet
• Clarification about research area remit, for example metamaterials doesn’t mean photonics
• Clear communication both ways (pre-proposal) minimising initial time
• CDT
• Capacity building – people
• EU various work programmes
  - to influence
  - or think about
• Funding from industry
• Innovate UK (high TRL ‘Link’ project)
• EPSRC to fund ‘extra students’ for areas that are priority
• DSTL (organise meetings to bring community together) – be more proactive in approaching people
• Korean - UK network in area (as with energy storage)
• NSF/US Universities
• Industry perspective and response £K
• Look at what Fraunhofer / Korea / Japan / France / China etc. are doing in this space. Talk to BIS about gathering this information.
• Investment strategy
• Develop strategic vision and lobby government using Tech UK etc.

**Who else needs to be involved e.g. other disciplines, users?**

• Space research community, STFC, Satellite Applications Catapult
• Life sciences
• Chemistry
• Physics
• Materials
• Manufacturing
• Bio-engineering, bio-driven / inspired approaches (BBSRC)
• Manufacturing engineering
• Biomedical - medics side
• Mimic design
• Modelling
• Geologists – using microwave to break up rocks
• KTN
• Innovate UK
• International collaborator – identify complementary areas
• European partners (who? – ESA, ERC, ‘CHIST-ERA’) H2020
• DFG/Fraunhofer
• FNSA (French space agency)
• Keysight (formerly Agilent Technologies)
• Industry for example semi-conductor foundry, Cambridge Silicon Radio, Tech UK – FTN, Teraview, NPL, UBLOX, defence industry

Summary and next steps

A number of outcomes arose from the workshop that specifically aligned with the objectives for the event. These outputs, as perceived by EPSRC, are described below:

• **Identify specific research challenges in RF and Microwave Devices in which new materials might lead to a step change in technology or performance.**

  o Nine high level research challenges in RF and microwave technologies where materials might lead to a step change in technology or performance were identified.

• **Identify classes of materials that have properties which offer potential for a step change in RF and microwave technologies and link these to the research challenges identified.**
Eleven materials-based groups which offer the potential to contribute to addressing research challenges in RF and microwave technologies were identified.

Links between the properties of materials and the research challenges in RF and microwave technologies to which they might contribute were identified.

- **Initiate future research collaborations and engagement by introducing researchers from the various communities in a neutral environment.**

The workshop brought together researchers from RF and microwave technologies and materials science. There was recognition during discussions at the event that the links between these communities should be strengthened.

- **Identify potential future actions which may facilitate collaboration between the RF and microwave technologies and materials communities.**

A number of actions for both the community (including users) and funders have been identified.

Potential future actions will be considered by the ICT Theme then discussed with other themes in EPSRC and the ICT Strategic Advisory Team.

In response to the points raised about increased community engagement all delegates have been sent the links to the workshop (http://www.epsrc.ac.uk/funding/howtoapply/routes/network/workshops/) and network (http://www.epsrc.ac.uk/funding/howtoapply/routes/network/networks/) scheme pages on the EPSRC website and encouraged to have a discussion with EPSRC should they wish to submit a proposal for either of these activities. It has also been stated that EPSRC would welcome proposals at the interface of RF and microwave technologies and materials through standard mode. The aspiration to strengthen links between these areas is described in the research area rationales for both the RF and Microwave Devices (http://www.epsrc.ac.uk/research/ourportfolio/researchareas/rfmicrodev/) and RF and Microwave Communications (http://www.epsrc.ac.uk/research/ourportfolio/researchareas/rfmicrocomms/) research areas.
## Appendix 1: Delegate list

<table>
<thead>
<tr>
<th>Title</th>
<th>Name</th>
<th>Institution</th>
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<tbody>
<tr>
<td>Dr</td>
<td>John Batchelor</td>
<td>University of Kent</td>
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<tr>
<td>Professor</td>
<td>Mark Beach</td>
<td>University of Bristol</td>
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<tr>
<td>Mr</td>
<td>Nigel Birch</td>
<td>EPSRC</td>
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<tr>
<td>Dr</td>
<td>Vivienne Blackstone</td>
<td>EPSRC</td>
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<tr>
<td>Dr</td>
<td>Liam Blackwell</td>
<td>EPSRC</td>
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<tr>
<td>Mrs</td>
<td>Sue Carter</td>
<td>EPSRC</td>
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<tr>
<td>Dr</td>
<td>Stuart Cavill</td>
<td>University of York</td>
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<tr>
<td>Professor</td>
<td>Xiaodong Chen</td>
<td>Queen Mary University of London</td>
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<tr>
<td>Dr</td>
<td>Gareth Conway</td>
<td>Queens University of Belfast</td>
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<tr>
<td>Professor</td>
<td>Adrian Cross</td>
<td>University of Strathclyde</td>
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<tr>
<td>Dr</td>
<td>Claire Dancer</td>
<td>University of Warwick</td>
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<tr>
<td>Professor</td>
<td>Merlyne De Souza</td>
<td>University of Sheffield</td>
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<tr>
<td>Dr</td>
<td>Rob Donnan</td>
<td>Queen Mary University of London</td>
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<tr>
<td>Dr</td>
<td>Khaled Elgaid</td>
<td>University of Glasgow</td>
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<tr>
<td>Dr</td>
<td>Peter Evans</td>
<td>Brunel University</td>
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<tr>
<td>Dr</td>
<td>Debbie Fellows</td>
<td>BAE Systems</td>
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<td>Dr</td>
<td>Alex Feresidis</td>
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<td>Dr</td>
<td>Martin Jones</td>
<td>STFC</td>
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<tr>
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<td>Heriot-Watt University</td>
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<td>Loughborough University</td>
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<tr>
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