Antenna Array Design Using Microwave Photonics Technology

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I gratefully acknowledge the support of:

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V. Hurm IAF Freiburg

Kharkov State Technical University of Radio Electronics
### Microwave Photonics – Impact and Applications

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Description</th>
<th>Applications</th>
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</thead>
<tbody>
<tr>
<td>$2 \text{ GHz} \leq f \leq 60 \text{ GHz}$</td>
<td>Electronic generation of spectrally pure microwave signals, inexpensive distribution to many receivers via optical fibres, local demodulation, inexpensive electronic amplification</td>
<td>Terrestrial communication (mobile phones, office, ”last mile”), radar, inter-satellite communication, sensors</td>
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<tr>
<td>$60 \text{ GHz} \leq f \leq 100 \text{ GHz}$</td>
<td>Electronic signal generation more difficult, electronic amplifiers not yet standard products</td>
<td>Radar, inter-satellite communication, sensors (distance)</td>
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<tr>
<td>$100 \text{ GHz} \leq f \leq 10 \text{ THz}$</td>
<td>Electronic signal generation uneconomical or impossible, no electronic amplifiers available</td>
<td>Radar, imaging, sensors, medical diagnostics</td>
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</table>
A look into the future: Terahertz Photonics – What are T-rays?

Quality control, medical diagnostics, gas spectroscopy

- Humidity (absorption lines 0.6 ... 2 THz, CLEO’98 CTuB5, Opt. Lett. 14 (1989) 1128): production of food
- Dermatology: Structure of burned skin without biopsy
- Tomography (Opt. Lett. 22 (1997) 904)
- T-rays replace Roentgen rays (X-rays): Imaging of “invisible” objects
  - Inspection of pallets
  - Airport safety measures, drug detection
- Analysis of flames and gases (toxicity, Fourier spectrum)
- Quality control: Holes in plastic parts, plastics for car production
- Radar applications (measurement of reflection)
Mixing of two optical signals by a Schottky photodiode

- 2 optical lines, difference frequency 10 THz
- Schottky diode as photodetector-mixer.
  Lateral dimensions in 1-µm range
  (Light focus dimension $0.61 \cdot \lambda = 1 \mu m$)
  Junction capacitance $C \approx 3 \text{ fF}$
  Series resistance $R \approx 5 \Omega$ (!)
  $RC$ corner frequency $f_c \approx 11 \text{ THz}$
- Integrated antenna, $\lambda$-dipole for 10 THz.
  High edge precision in nm-range necessary
- Receiving antenna with similar structure as detector of T-rays

Technological Problems and Challenges

- Electrochem. nano-structuring of Schottky PD: Substrate n-Si; metal (e.g. Pb); junction $C$; series $R$
- Corrosion and passivation, accuracy, edge precision, and transmission line loss (type e.g. coplanar)
Microwave Photonics – What Can Hybrid Techniques Do?

**Micro and picocellular networks (HFR, Hybrid Fibre Radio)**

*Operation principle:*
Data signals modulated on optical carrier, via low-loss fibre transmitted, in base station demodulated and radiated.

Few expensive *control stations* with frequency-stable microwave generators, numerous inexpensive *base stations* with opto-electronic converters and MMIC microwave amplifiers.

- Local Multipoint & Multipoint Video Distribution System (LMDS & MVDS)
- Mobile Broadband Systems (MBS)
- In-House, shop, and hangar systems
- Telematics, sensors, military and satellite communication
Example of HFR Control and Base Stations
Antenna array beam steering and squint

- Antenna array modelled by linear array of point sources (\( \bullet \), `grating´ constant \( d \)), \( \delta \varphi = 0 \)
- Propagation in 1st diffraction order direction, tilted from normal \( \vartheta = 90^\circ \) by \( \delta \vartheta \)
- Well known diffraction formula \( \sin(\delta \vartheta) = \frac{\lambda_m}{d} \)
- With arbitrary \( \delta \varphi \) at \( \bullet \), 0th order beam direction tilted by:
  \[
  \sin(\delta \vartheta) = \frac{\lambda_m}{d} \frac{\delta \varphi}{2\pi} = \frac{c}{\omega_m} \frac{\delta \varphi}{d}
  \]
- If subcarrier \( f_m \) varies with time \( t \): beam squint \( \delta \vartheta(t) \) for \( \delta \varphi = \text{const}_t \)
- No squint even with wide bandwidth signal, if
  \[
  \delta \varphi \sim \omega_m
  \]
  for all \( \omega_m \)

Problems with RF beamforming network (BFN):
- High losses, high dispersion, interference with microwave transm. lines and fields, bulky, complicated mechanical arrangement
Antenna Array, Beam Squint, and Beamforming Network (2)

Recipe for RF transmission and optical beamforming network

- 2 optical lines, difference frequency $f_m = 20 \text{GHz}$
- RF modulation signal transferred to one of the optical lines
- Transmit by optical single-mode fibre
- Detect original RF signal from optical carrier by mixing modulated and unmodulated line
- Mixing by detecting optical power with photodetector (quadratic demodulator, but no sum frequency!)
- Photocurrent contains the IF $f_m = f_2 - f_1$
- Amplify the photocurrent
- Radiate resulting signal by each antenna element
- Adjust the beamforming network by the lengths $L$ of the optical fibres, either mechanically, or optically

**Beauties of optical TTD**

- Low volume, light, inexpensive
- Very low loss, very low dispersion

**Recipe Diagram**

- $f_m = f_2 - f_1 = 20 \text{GHz}$ (15 mm)
- $\frac{1}{2} \lambda/n = 5 \text{mm}$
- 1.55 µm / 193 THz
- 600 µm

**Fibre Transmission, length $L$**
Avoiding beam squint by TTD

**TTD schematic (True Time Delay Network)**

- Linear array modelled by linear array of point sources $\bullet$, fed at $\circ$ with identical phases by delay lines of length $L_i = L + i\delta L$ with length increments $\delta L$.
- RF current phase difference at $\bullet$ expressed by group delay time increment $\delta t_g$ or, with group velocity $v_g$, by
  \[
  \delta \varphi = \omega_m \delta t_g = \omega_m \frac{\delta L}{v_g}
  \]

**No beam squint**

- With arbitrary $f_m$ and $\delta L$, 0th order beam direction tilted by
  \[
  \sin(\delta \vartheta) = \frac{\lambda_m}{d} \frac{\delta \varphi}{2\pi} = \frac{c}{\omega_m} \frac{\delta \varphi}{d} = \frac{c}{v_g} \frac{\delta L}{d}
  \]

- Microwave photonics makes *optical* feeder network possible, greatly reduces problems of a true time delay (TTD) network:
- Low losses, low dispersion, not bulky, no interference with microw. transm. lines & fields
RF Signal Fibre Transmission

Details of RF transmission over dispersive single-mode fibre

Transfer function of opt. transm. fibre, length \( L_i \):
\[
\tilde{h}_i(f) = \exp[-j \beta_i(\omega)L_i]
\]

Feeds opt. receivers \( \rightarrow \) RF drive of antenna elem.
Prop. const. \( \beta \), group delay time \( t_g/L = 5\mu s/km \),
chromatic dispersion \( C = 17\, \text{ps/}(\text{km nm}) \):
\[
\beta_i \approx \beta(\omega_0) + (\omega - \omega_0) \frac{t_g}{L_i} - \frac{(\omega - \omega_0)^2}{2} \frac{\lambda_0^2}{2\pi c} C
\]
Fibre length incr. @ RF mod. freq. \( f_m = 20\, \text{GHz} \):
\[
\delta L_{\text{max}} = \frac{v_g}{c} d = \frac{2}{3} \frac{\lambda_m}{2} = \frac{15}{3} \text{mm} = 5\, \text{mm}
\]

Group delay time increment:
\[
\delta t_{g_{\text{max}}} = \frac{\delta L_{\text{max}}}{v_g} = \frac{d}{c} = \frac{\lambda_m}{2c} = \frac{1}{2f_m} = 25\, \text{ps}
\]

Chrom. delay time err. for spectr. width \( \Delta f = f_m \):
\[
\Delta f = 20\, \text{GHz}, \quad \Delta = \frac{(1.55\, \mu\text{m})^2}{c} \Delta f = 0.16\, \text{nm}
\]
\[
\delta t_{g_{\text{c}}} = C \delta L_{\text{max}} \Delta \lambda = 14\, \text{fs} = 0.6 \times 10^{-3} \delta t_{g_{\text{max}}}
\]

Summary:
Chromatic dispersion unimportant for OBFN

Fibre output spectrum from transfer function:
\[
\tilde{\alpha}_L(f) = \tilde{h}(f) \left[ \delta(f - f_1) + \delta(f - f_2) \right]
\]

PD detects opt. power (quadr. demodul. for \( f_m \),
no optical sum frequency!), RF current \( i(t) \):
\[
i(t) \propto \left| F^{-1}\{\tilde{\alpha}_L(f)\} \right|^2 \propto \cos(\omega_m t - \omega_m t_g - \varphi_{\omega_m t_g})
\]
Each of 3 antenna elements separately fed via single-mode glass fibre, which illuminates PD from top.
HEMT Photoreceiver (IAF, Hurm et al. ECOC 1998)

- OEIC on semi-insulating GaAs (2.5 mm × 1 mm)
- PD 10 µm∅, 3-dB bandw. 36.5 GHz @ 25 Ω, RC limited (- - -)
- Distributed amplifier with 4 HEMT stages
- Cascoded pseudomorphic HEMT
  Gate length 150 nm, InGaAs channel 12 nm
  Transconductance $g_m = 754$ mS / mm, current-gain cut-off frequency $f_T = 90$ GHz,
  Maximum oscillation frequency $f_{max} = 150$ GHz
  Coplanar 50- Ω output
Coplanar $\lambda$-dipole at 20 GHz

**Electric field at coplanar dipole**

**Radiation pattern and input impedance**

- Radiation pattern
- Input impedance

- **Diagram Details**: Diagram showing the electric field and the radiation pattern at 20 GHz. The diagram includes graphs for the electric field ratio $\frac{|E_0|}{E_{0,\text{max}}}$ and the magnitude of $S_{21}$ against frequency. The radiation pattern is shown for both electrical and optical modes.
Summary and Outlook

Present state

- Data transmitted to base stations via photonic networks
- Application of MWP (here: at 20 GHz) mainly for radio communication and sensors
- Mass market for bridging the “last mile” for connecting subscribers to broadband communication networks without road works
- With optical beamforming networks, the radiation patterns don’t show "beam squint"
- Length reconfiguration of fibre feeders for spatial beam tracking

Microwave photonics

- Upgrade of model system from 20 GHz to higher frequencies, e.g., 40 GHz
- Design and test of optical beamforming networks
- Antenna design for semiconductor substrates with refractive indices near $n = 3.6$
- Problems: Radiation efficiency
- Amplifier heat removal

Future work

Future Terahertz Photonics

- Design of THz transm. lines with edge precision in the 4-nm region on semicond. substrates; losses
- Design and investigation of photo-sensitive Schottky diodes
- Antenna design