A Compact K-Band High Data Rate Upconverter / Solid State Power Amplifier (SSPA) Downlink Engineering Model for LEO Missions

Jim Mayock[#1], Thomas Le Toux[#], Simon S. M Chan[#], Pratik Deshpande[#], Tuyen Vo[#], Farshad Eshghabadi[#], Matthew O'Keefe[#], Ken Mason[$2], David Sanderson[$], Iain Davies[*3]

[#]VIPER RF Limited, Newton Aycliffe, UK
[$]Surrey Satellite Technology Limited, Guildford, UK
[*]TEC-EF, ESTEC, Noordwijk, Netherlands
[1]jim.mayock@viper-rf.com, [2]kmason@sstl.co.uk, [3]iain.davies@esa.int

***Abstract* — An engineering model of a Ka-Band transmitter downlink module for LEO satellites has been developed. The module consists of a custom MMIC chipset, LO circuit module, RF filtering and associated module control electronics. The MMIC chipset consists of an IF attenuator, up-converter, driver MPA and HPA. The HPA exhibits a peak output power of approximately 41dBm with an associated PAE of 25% in the 25.5-27GHz band. The MPA has a small-signal gain of greater than 27dB with an output power > 31dBm. The up-converter MMIC has a conversion gain of approximately 25dB with compliant spurious performance and the attenuator MMIC provides 6-bit control. The MMICs are mounted onto a 4-layer RF substrate and copper inserts provide a low thermal resistance between the package and module baseplate. The output from the MMIC PCA feeds a PCB-WR34 transition mounted underneath the PCA, this in turn feeds the waveguide filter. The LO is based on a fractional-N Ku-band PLL with a high stability low noise TCXO as the reference and has ALC circuitry to maintain a constant LO level. The module delivers 37.5dBm of linear output power for modulations up to 16-APSK and 36.1 dBm for 32-APSK. The DC power consumption is 55W from 28V.**

***Keywords* — MMIC, Ka-band, power amplifiers.**

I. Introduction

The increasing quantity of data collected and required for downlink from Earth Observation (EO) Low Earth Orbit (LEO) satellites and the congestion at X-Band has led to a move to the 25.5-27GHz Ka-Band frequencies [1-4]. The X-Band spectrum (8.025-8.4GHz) is currently used to achieve downlink user data rates in the region of 500Mbps per channel. Therefore, the 1.5GHz spectrum allocated for EO in Ka-Band is attractive for applications requiring high data rate telemetry, beyond the 1Gbps range. The development of a customized MMIC (Microwave Monolithic Integrated Circuit) chipset and Ka-band Upconverter/SSPA (Solid-State Power Amplifier) module is discussed here.

Traditionally, space-qualified GaAs technologies have been used to provide solid-state transmitter solutions at millimeter-wave frequencies. With the advent of short gate-length GaN solutions with up to five times the power density of the same geometry GaAs technologies, a wider range of solid-state transmitter solutions can be considered. Presently, several GaN technology options are available from European suppliers such as the GH15 (GaN-on-SiC) from United Monolithic Semiconductors (UMS) and the D01GH (GaN-on-Si) technology from MACOM. These technologies are capable of providing >10W of peak output power from a single chip with ECSS (European Cooperation for Space Standardization) de-rating levels. The lower power functions can be realized on more cost-effective GaAs technology.

The Ka-band Upconverter/SSPA module developed here is a payload subsystem dedicated for high data-rate LEO missions, capable of transmitting a range of modulated output powers up to approximately 10W. The module accepts an input IF frequency of 7.8-8.6GHz, upconverted to the RF output range of 25.5-27GHz, split into two sub-bands with a selectable LO frequency of 17.0375GHz and 17.4125GHz. The LO is generated internally by a PLL (phase-locked loop). The transmit chain accepts several input modulation formats ranging from QPSK and 8-PSK to 32-APSK, with internal selectable gain through a 6-bit digitally-controlled attenuator to operate at the appropriate output power level. In operation, the unit power added efficiency is 14%. The unit also features a beacon-mode operation, capable of an accurate output power of 0.43Wrms, selectable through a simple bias control. The module is of dimensions 135 x 206 x 35 mm, and features an input IF SMA connector, and an output WR-34 waveguide connection after internal RF channel waveguide filtering and is designed to interface with an SSTL bias and control unit.

II. MMIC Design and Test

The architecture for the Ka-Band transmitter solution is shown in Fig. 1; this solution is comprised of four MMICs which have been designed to operate in SMT metal-ceramic packages and for use in bare die form. The MMIC chipset has been designed to meet space de-rating requirements.

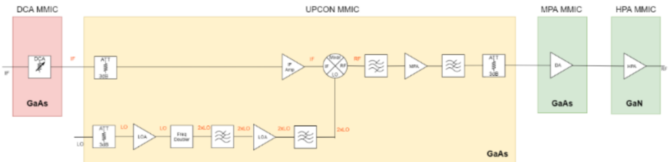
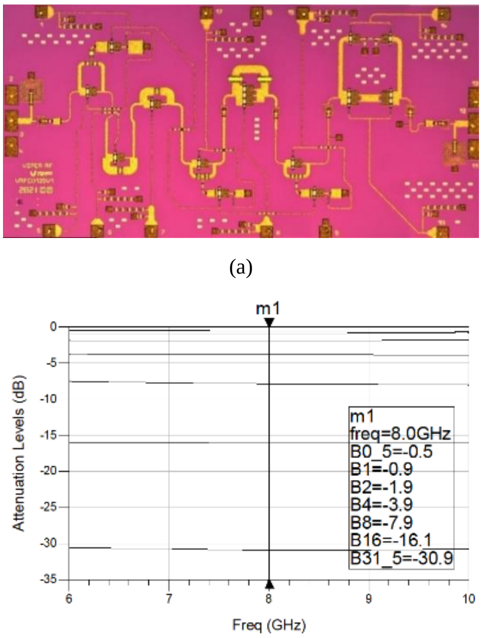


Fig. 1. Line-up for the Ka-Band transmitter solution

A. Digital Controlled Attenuator (DCA) MMIC

A 6-bit digitally controlled IF attenuator MMIC was developed on the UMS PPH15X 0.15um GaAs process to provide 31.5dB dynamic range with 0.5dB minimum step size. The lowest attenuation steps were realized by simple switch FETs in parallel with resistors, the mid-range attenuation with shunt switch/resistors, and SPDTs are used for the 16dB bit. An insertion loss of approximately 8dB with return losses >13dB is achieved in the 7.8-8.6GHz IF band for all major states. The attenuator exhibits excellent attenuation control with an RMS attenuation error of approximately 0.15dB. Fig. 2 shows a micrograph of the manufactured MMIC and measured attenuation levels of the major states.



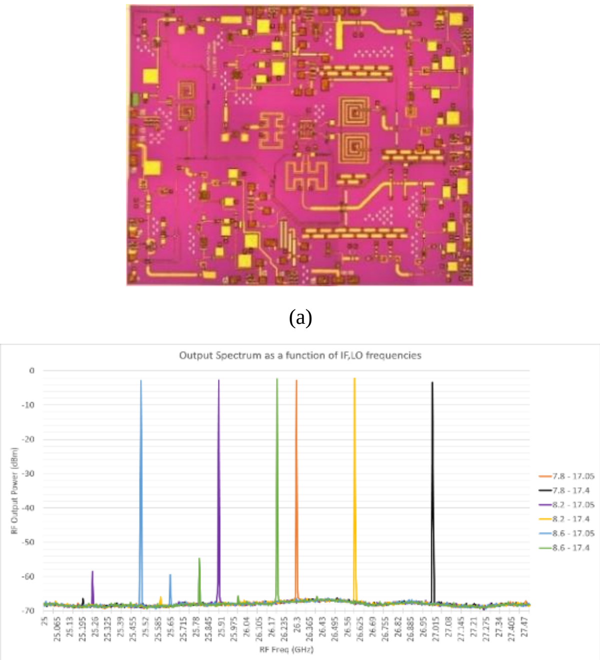
(a)

(b)

Fig. 2. IF Attenuator MMIC (a) Micrograph; (b) measured attenuation of major states

B. Upconverter MMIC

An upconverter MMIC, also developed on the UMS PPH15X technology, mixes the Ku-Band LO input signal with the X-Band IF signal to provide the RF output. The key aspect of the up-conversion process is to minimize the spurious signal generation, particularly of components which fall in the RF band and cannot be filtered. In the present design, a high-side LO approach offers a good rejection of the in-band spurious components. The LO chain comprises of the frequency doubler, Ku-Band and Ka-Band LO amplifiers and some simple stepped attenuation to maintain constant power into the mixer over temperature. The IF stage is based on a simple two-stage amplifier. The RF chain is based on a three-stage amplifier and some on-chip filtering. The mixer is based on a double-balanced ring FET configuration which provides a natural rejection of key spurious frequency components [5]. The upconverter showed a measured conversion gain of approximately 25dB with IF, LO and RF return losses greater than 15dB, 10dB and 12dB respectively. The MMIC has been characterized over a range of LO and IF frequencies. A micrograph of the manufactured MMIC and an example of a set of output spectrums are shown in Fig 3. Each of the larger output signals corresponds to a different combination of LO and IF frequencies which are outlined in the legend. The lower signal levels are spurious signals and are related to an RF output signal by colour. In each case the in-band spurious signals are less than the requirement of 45dBc. Other out-of-band signals are filtered by the RF output filter. The simulated conversion gain is approximately 3dB lower than measured. However, this is deemed acceptable based on the complexity of the LO chain and mixer, the number of gain stages in the IF and RF sections, and still meets the gain specification of the system.



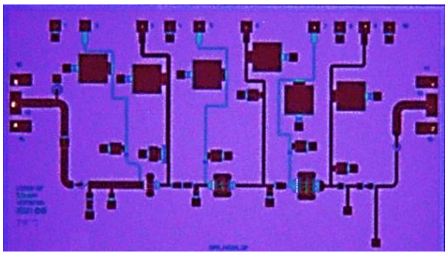
(a)

(b)

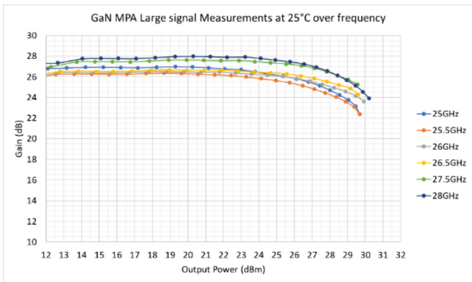
Fig. 3. Upconverter MMIC: (a) Micrograph; (b) Spectral measurements as a function of LO and IF Frequencies

C. Medium-Power Amplifier (MPA) Driver MMIC

A MPA driver MMIC was developed on the UMS GH15-10 GaN-on-SiC technology. The MPA is a three-stage design based on a 4x50um input cell, a 4x125um cell in the second stage and the output stage is realized by a 6x135um cell. A gain of approximately 27dB is achieved with input and output return losses greater than 12dB in the Ka-Band. The large-signal performance is shown in Fig. 4. An output power of greater than 30dBm is achieved which is sufficient to drive the HPA.



(a)



(b)

Fig. 4. MPA MMIC: (a) Micrograph; (b) Large Signal Measurements at Vd=20V, Id=220mA

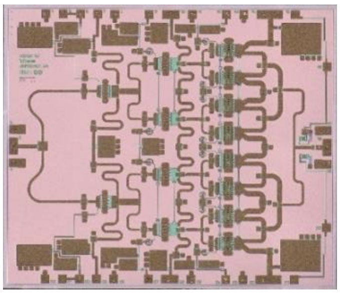
D. High-Power Amplifier (HPA) MMIC

The MMIC HPA is a three-stage design based on a 8x6x125um output stage, a second stage based on a 4x6x125um configuration and a 2x4x125um first stage. An integrated power detector based on a coupled line/diode configuration was employed in the output. Photographs of the manufactured MMIC chipset are shown in Figure 5. A measured gain of approximately 28dB with return losses of greater than 13dB in band was achieved. The measured versus modelled performance shows good agreement for all parameters. Fig. 5(c) shows the on-wafer pulsed measurements; an output power of approximately 41.5dBm is achieved across all devices on the wafer. It is worth noting that the on-wafer measurements do not include the impact of the package/bond-wire. The measured CW output power and PAE as a function of swept input power is shown in Fig. 11. A peak output power of approximately 41dBm with a PAE of 25% is achieved. Under backed-off conditions a PAE level of approximately 20% is achieved at a HPA transmit power of 39.1dBm.

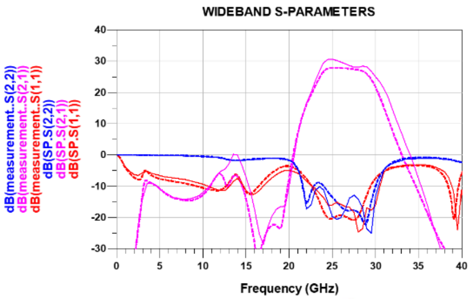
III. Module Design and Test

The module consists of the following key elements: local oscillator printed circuit assembly (PCA), MMIC PCA, waveguide transition and output filter on the lower level of the module and a separate power supply sub-module on the upper level. Fig. 6 shows photographs of the assembled Ka-band module.

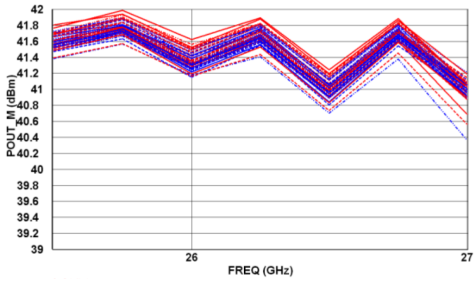
The key challenges for the module technological and design approach can be summarised as follows:



(a)



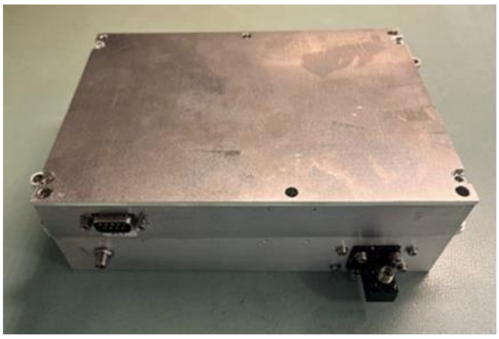
(b)



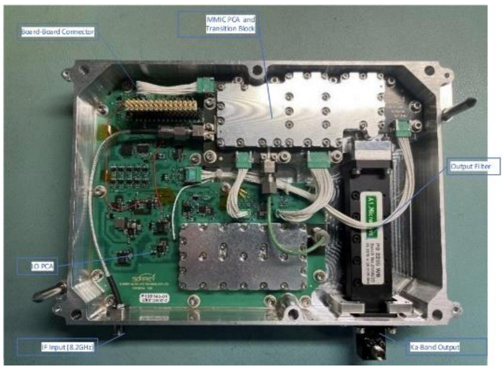
(c)

Fig. 5. HPA MMIC: (a) micrograph; (b) S-parameters and (c) Large Signal Measurements at Vd=20V, Id=1000mA

- LO PCA: Low noise local oscillator with tight power control requirements (±2 dB). The PLL (phase locked loop) was designed for low phase noise, using fractional-N to reduce the multiplicative phase noise. An ALC (automatic level control) loop, locked to an accurate power detector provided an adjustable and stable output level over temperature.
- MMIC PCA: Integration of custom four MMIC chipset described above. Thermal path from the backside of the MMIC package to the baseplate required the use of copper inserts to provide a low thermal resistance.
- PCB-WR34 transition: Integration of transition into the MMIC PCA block to minimise insertion loss in the output stage and provide a good return loss over the full 1.5GHz band; this was achieved through extensive use of 3D EM (electromagnetic) simulation using Feko and careful attention to critical mechanical dimensions in the feed structure.



(a)



(b)

Fig. 6. Ka-band Module Photograph (a) Full module; (b) Module with lid removed (power supply unit sub-module removed)

A. *Local Oscillator*

The LO phase noise performance is one of the key metrics; Fig. 7 shows a plot of the measured vs. the predicted phase noise taken at the LO output at Ku-Band. The LO output power was set at 1.2dBm and this varied from 1.5dBm @ -20°C to 1.3 dBm @ 50°C. The small variation was achieved with a power control loop and envelope detector, the latter with a highly stable temperature characteristic.

B. *Upconverter Module Performance*

The key performance metric for the upconverter is the Bit Error Rate (BER) versus the normalized signal-to-noise ratio (Eb/No) at the operating output powers of 37.5 dBm and 36.2 dBm. The performance was evaluated using SCCC (Serial concatenated convolutional codes) encoding @ 400MBd for all modulations, this is compared with a baseline measurement (loop-back) of the test system at 350 MBd. Fig. 8 shows a plot of the measured output BER versus Eb/No for a range of modulation schemes at a data rate of 400MBd. BER performance close to the test baseline is observed for QPSK, 8-PSK, and 16-APSK modulations. The degradation in performance at 32-APSK is due to degraded EVM (Error Vector Magnitude) as a result of distortion in the HPA; pre-distortion is being investigated to improve performance at 32-APSK.

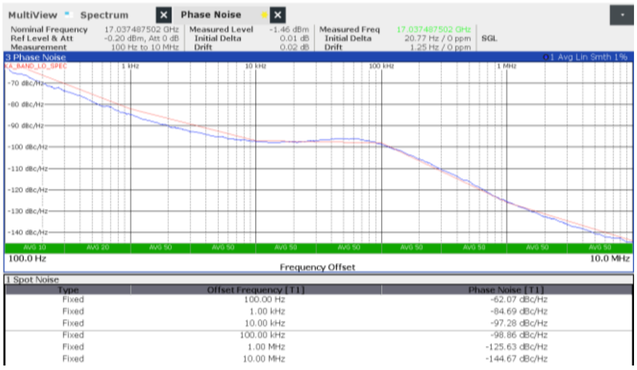


Fig.7. Measured versus modelled LO Phase Noise @ 25°C, 17.0375 GHz

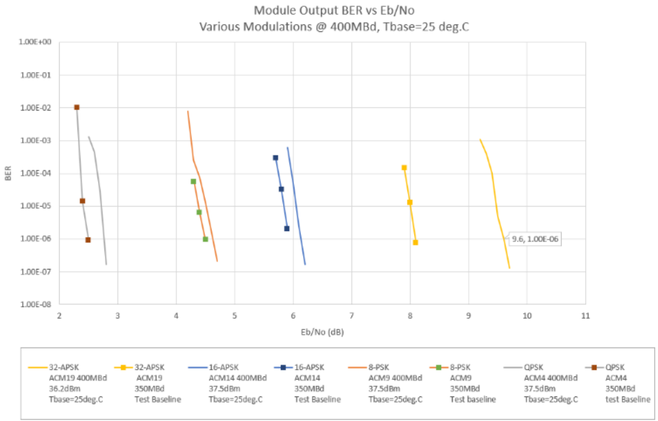


Fig. 8. Module Output BER vs Eb/No for all Modulations @ 400MBd

IV. Conclusion

A space de-rated Ka-band MMIC chipset consisting of GaAs DCA and upconverter, and GaN-on-SiC MPA and 10W HPA functions has been designed, manufactured and characterized. The MMIC chipset has been configured into a compact upconverter/SSPA module targeted for LEO satellite small missions. The module showed good BER performance for modulations up to 16-APSK. Additional linearization is being investigated for 32-APSK and higher order modulations.

References

[1] J. Roselló, A. Martellucci, R. Acosta, J. Nessel, L. E. Bråten and C. Riva, "26-GHz data downlink for LEO satellites," 2012 6th European Conference on Antennas and Propagation (EUCAP), Prague, Czech Republic, 2012, pp. 111-115, doi: 10.1109/EuCAP.2012.6206717.

[2] M. Jeffries, K. maynard, P. Garner. J. Mayock, P. Deshpande, "26-GHz data downlink and RF beacon for LEO in orbit demonstrator satellite", 2016 International Workshop on Tracking, Telemetry and Command Systems for Space Applications (TTC), 2016, Noordwijk

[3] I. Rosello, A. Martellucci, R. Acosta, I. Nessel, L.E. Braten and C. Riva, "26-GHz Data Downlink for LEO Satellites", 6th European Conference on Antennas and Propagation (EUCAP), March 2012.

[4] N. Toptsidis, P.-D. Arapoglou and M. Bertinelli, "Link adaptation for Ka band low Earth orbit Earth Observation systems: A realistic performance assessment" in Int. J. Satell. Commun. Network, Published online, vol. 30, pp. 131-146, 2012.

[5] H. -C. Yeh, C. -C. Chiong, M. -T. Chen and H. Wang, "Review of Millimeter-Wave MMIC Mixers," in IEEE Design & Test, vol. 31, no. 6, pp. 38-45, Dec. 2014, doi: 10.1109/MDAT.2014.2360451.