group delay slope of nearly 900ps/nm was used. To avoid the CFG dispersion-induced effects on the filter response the RF input filter signal drives an optical single sideband modulator composed of a dual-electrode MZ-EOM and a 90° hybrid coupler [7]. By driving the EAM with a 16GHz frequency tone with a power of +20dBm a filter response centred at nearly 9GHz with a –3dB bandwidth of 2GHz was obtained, as shown (solid line) in Fig. 2. The output power of the DFB laser was 3dBm. The EAM reverse bias voltage was set at 3V. The simulation result is also depicted in Fig. 2 (dashed line) and very good agreement is observed with the experimental results. In Fig. 2 it can be seen that the rejection ratio (peak-to-valley ratio) outside the passband of the filter is nearly 30dB. This Figure shows a very good performance of these filters as compared to other techniques [2] mainly due to the correlation of the optical modes produced by the EAM-based multimode optical source.

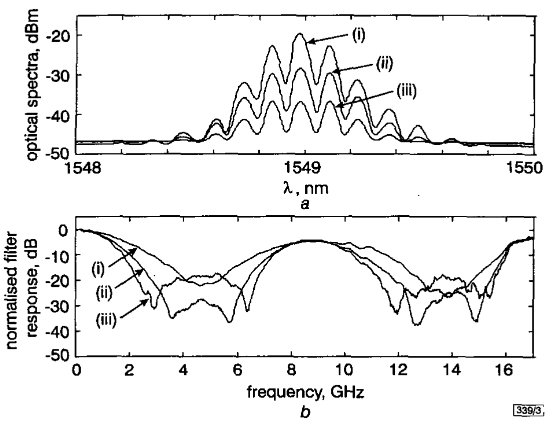

Fig. 3 *Measurement of optical spectra at EAM output for different reverse bias voltage, and frequency response of filter for different EAM reverse bias voltages*

(i) 1.5V, (ii) 3.5V and (iii) 4.5V
a Optical spectra
b Frequency response

To demonstrate the impact of the spectral envelope of the optical modes generated by the EAM on the filter response, the EAM bias voltage was varied. Fig. 3*a* shows the measured optical spectra at the EAM output for different bias voltages, and the filter responses for those bias voltages are depicted in Fig. 3*b*. In Fig. 3*a* and *b* it may be observed that a higher frequency selectivity of the filter response may be achieved by properly adjusting the EAM bias voltage to broaden the envelope of the optical spectrum generated by the EAM. This result is consistent with the classical theory of digital filter design [8]. However, the rejection ratio of the filter may be optimised by selecting a certain EAM bias voltage. These results show that the photonic microwave filter response may be readily reconfigured by adjusting the EAM bias voltage.

Conclusion: A novel photonic tunable microwave filter employing electroabsorption modulators and wideband chirped fibre gratings has been proposed and demonstrated. The simulation and experimental results show very good agreement. It is shown that, by varying the EAM bias voltage, the shape of filter response as well as its frequency selectivity may be readily reconfigured. The tunability of the filter may be accomplished by changing the frequency of the tone driving the EAM.

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Printed analogue filter structures

P.S.A. Evans, B.J. Ramsey, P.M. Harrey and D.J. Harrison

The authors report progress in conductive lithographic film (CLF) technology, which uses the offset lithographic printing process to form electrically conductive patterns on flexible substrates. Networks of planar passive components and interconnects fabricated simultaneously via the CLF process form notch filter networks at 85kHz.

Conductive lithographic films: The conductive lithographic film (CLF) process is used to fabricate electrical conductors on a wide range of flexible substrates (e.g. paper of polymer film) using a specially formulated silver-loaded ink and a standard lithographic printing press [1]. The ink developed for the CLF printing process consists of a suspension of metallic silver particles in an organic resin. Although this resin is non-conductive, it acts as a vehicle for the conductive particles and partly determines the rheological properties of the ink. The current ink formulation contains a high proportion (~ 80% w/w) of a silver metal flake with a mean particle size of ≤ 1μm.

Printed CLF ink films consist of a thin layer (~ 3μm) of silver particles suspended in the organic resin ink binder, and possess sheet resistivities of ≤ 0.25Ω/□, which is comparable with thick-film circuit practice. The films can be overprinted if necessary with excellent registration (typically within 25μm), and track-and-gap spacings of 100μm are readily achieved (Fig. 1). Conductive lithographic films are cheap to produce and are also robust, withstanding standard circuit board environmental test regimes [1]. CLF circuit boards have been successfully employed in a range of analogue, microprocessor and microwave circuit applications [2, 3].

Passive component printing: The finite sheet resistivity of CLF conductors indicated that a wide range of 'meander' resistors could be manufactured by printing thin elongated circuit tracks. Low value capacitors could also be formed from arrays of interdigitated CLF lines printed at the minimum track-and-gap spacing. Printing trials on a well-filled paper substrate confirmed that resistors in the range 1kΩ – 100kΩ could be manufactured with absolute tolerances of 10%, and that the relative tolerance of resistors printed on the same substrate was ~ 1%. These results suggested that viable planar RC filters could be fabricated on flexible substrates via the CLF process, with all circuit components and interconnects formed in a single printing operation.

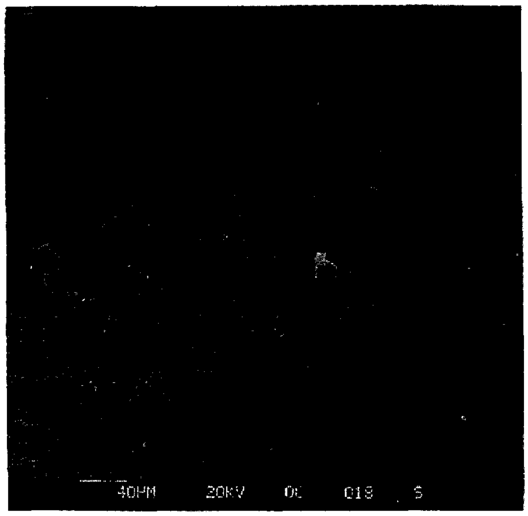

Fig. 1 *Micrograph of CLF track on polymer substrate*

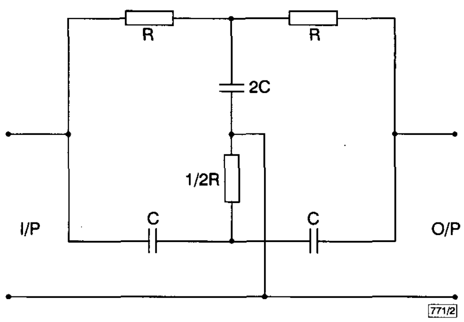

Fig. 2 *Twin-T filter circuit*

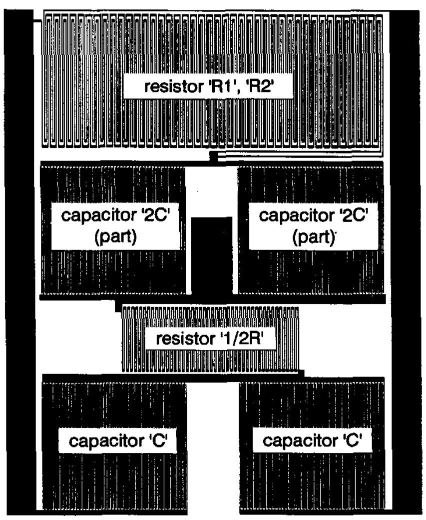

Fig. 3 *Printed twin-T filter design*

CLF filter design criteria: The familiar 'twin-T' notch filter consists of a network of three capacitors and three resistors (Fig. 2). This filter network sums two versions of the input signal, the amplitude and relative phase of which have been modified by the transfer function of the components. At one specific frequency (the notch frequency), these signal portions are of equal amplitude and opposite phase, and sum to produce a null output. The filter components determine this 'notch' frequency by the rule: $f_n = 1/2\pi RC$. Where the component values adhere precisely to the ratios indicated in Fig. 2, the attenuation of the filter at the notch frequency is infinite. Normal component production tolerances result in a finite notch attenuation; typically, several orders of magnitude of attenuation can be readily achieved.

The structure of the lithographically printed 'twin-T' filter design is depicted in Fig. 3. This filter is constructed using convoluted fine CLF tracks for the resistor elements (having a design resistance of 20kΩ), and blocks of interdigitated tracks producing the circuit capacitors (design value of 100pF). The I/O terminations of the filter are the broad stripes of conductor visible at the edges of the structure.

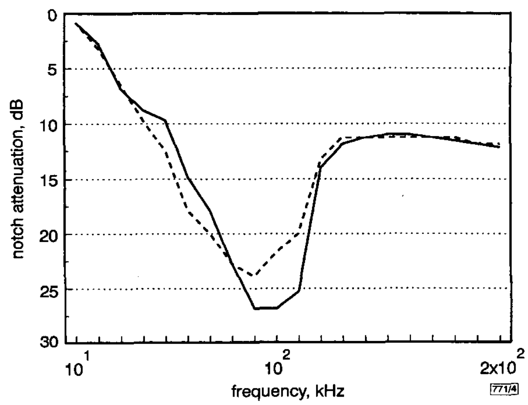

Fig. 4 *Planar filter frequency response*

The effect of minor variations in sheet resistivity of the conductive ink films, noted in a direction perpendicular to that of printing, was minimised by designing the two larger value filter resistors as a single structure, and aligning the smaller resistor structure, such that any global variation in sheet resistivity equally influenced all filter resistors. Provision was also made in the design of the larger resistor structure to make small adjustments to the initially printed value by bridging resistor track sections with conductive paint.

Results: The printed 'twin-T' filter structures were visually examined for printing defects, and were then evaluated using standard test instruments. A signal generator operating in the range 10–250kHz applied a sinusoidal signal to the input of the filter, while an oscilloscope fitted with a high impedance probe measured the amplitude of the output signal. Typical notch attenuations of ~26dB, at frequencies of ~ 85kHz, were observed in the functional structures. Two representative filter frequency response plots are depicted in Fig. 4. The dashed line represents the response of an unadjusted filter, the resistive elements of which exhibit tolerances typical of the CLF process. The solid plot represents the response of a filter whose resistors were manually adjusted in value using a conductive paint to compensate for printing variations.

Conclusions: The conductive lithographic film fabrication process has been employed to fabricate passive filter structures on flexible polymer substrates in a single printing operation. The filters were evaluated in an 'as printed' state and following manual correction of the printed resistor values. No attempt was made to adjust the values of the printed capacitors. Similar filter structures have been manufactured on various substrate materials including paper and flexible polymer sheets.

Notch attenuations of 25–30 dB have been recorded in measurements on the structures, and the bandwidth of the structures is ~ 30kHz. Applications of this work are considered to be primarily in low cost, light weight filter circuits and systems. However, values of the printed components (and hence the characteristics of the printed filter structures) are influenced by the water content of the substrate material. In unprotected substrates, water content is proportional to the local humidity, hence a further application of this work may lie in printed humidity sensors.

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Self-aligned GaAs JFETs for low-power microwave amplifiers and RFICs at 2.4GHz

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Self-aligned GaAs junction field effect transistor (JFET) narrowband amplifiers operating at 2.4GHz have been designed and fabricated both with discrete JFETs as a hybrid amplifier and as radiofrequency integrated circuits (RFICs). Enhancement-mode JFETs were used in order to be compatible with complementary digital logic. Hybrid amplifiers achieved 8–10dB of gain at 2.4GHz and 1mW DC bias level. The RFIC achieved 10dB of gain at 2.4GHz and 2mW DC bias level.

Introduction: Low power circuitry is very important for battery powered electronic components. While the low power operation of digital circuitry is taken for granted owing to the unique advantages offered by CMOS architectures, microwave circuits have no equivalent low power circuit configuration, require quiescent bias, and consequently have been reported infrequently in the literature. Commercial GaAs MESFET foundry technology was used to design and fabricate an amplifier with 15dB of gain for two stages with 0.8mW power at 1.25GHz [1]. An HFET (heterostructure field effect transistor) amplifier RFIC (radio frequency integrated circuit) achieved 10dB of gain at 0.5mW and 900MHz [2]. Amplifiers that operate at 1mW power level or lower have not been reported previously at higher frequencies.

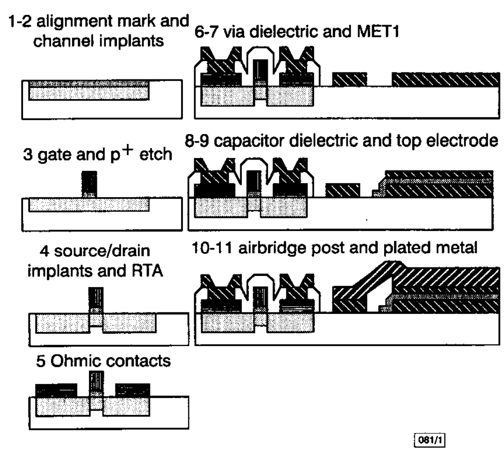

Fig. 1 *Process sequence for JFET RFIC*

Experiment: This work was adapted from a digital CHFET (complementary HFET) process [3] so as to ultimately provide for integrating microwave and digital functionalities. Passive elements including ion implanted GaAs resistors, SiN dielectric capacitors with 560pF/mm^2 capacitance, and airbridge inductors were introduced into the CHFET process so as to make the RFIC fully compatible with digital ICs. Both discrete JFETs (junction field effect transistors) and RFICs were fabricated according to the process illustrated in Fig. 1. Steps 1-5 illustrate the JFET fabrication. After alignment mark formation, channel implantion is performed using Si ions for the channel, Mg for backside confinement, and Zn for the p^+ region of the JFET gate [4]. The W refractory gate ($0.7 \times 100\mu m^2$ in this work) is defined and the p^+ region is etched away in the source and drain regions of the JFET. The Si ion implants for the self-aligned source/drain regions and the implant activation anneal then follow. JFET active regions are completed by Ohmic contact formation. The implant and Ohmic contact steps also serve to make the GaAs implanted resistors, with a sheet resistance of 400Ω/□. Steps 6-11 concern the fabrication of the transmission lines and the passive elements for an RFIC. The JFETs are passivated with SiN dielectric by plasma enhanced chemical vapour deposition (PECVD) and via holes are opened to contact the JFET gate and Ohmic metals. Ti/Pt/Au deposition and liftoff are carried out for the first metal which contacts the JFETs and also the GaAs substrate directly in the RFIC regions transmission lines and passive elements. The capacitor dielectric, SiN, is then deposited by PECVD. Patterning and deposition for the capacitor top electrode, a Ti/Pt/Au evaporation and liftoff then follow. Airbridge post definition followed by patterning and electroplating of the airbridge and transmission line metal complete the frontside processing. The final fabrication steps consist of wafer thinning to 100μm, backside electroplating, die separation, and assembly. Frontside bondwires are used for grounding the RFIC. Microwave gain and return loss measurements were carried out using an HP 8510C network analyser using Cascade Microtech microwave probes calibrated using a TRL calibration.

Hybrid amplifier: An n-channel JFET was evaluated as a microwave device. This self-aligned JFET has previously been shown to operate with performance comparable to a MESFET of the same gate length [4]. A narrowband amplifier was selected as a test vehicle since its successful implementation demonstrates the feasibility of most RFIC functions. The low power digital applications require low bias voltages ($V_{DS} \simeq 1$V), a small positive gate threshold, and large gate turn-on voltages (>1V). These design parameters are also ideal for low-power microwave applications. The voltages are very suitable for battery operation on a single cell and the positive gate threshold along with the large positive gate turn-on voltage eliminate the need for a negative supply as commonly required with MESFETs. Though not explicitly designed for microwave operation, the JFET shows impressive low power microwave properties with f_t > 13GHz and f_{max} > 20GHz, measured at the 1mW DC bias level.

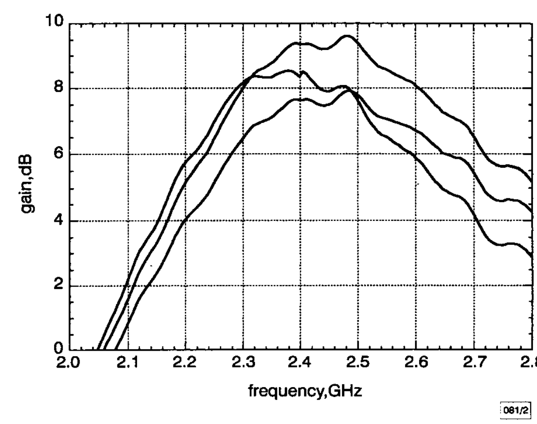

Fig. 2 *Gain characteristics of four packaged and three chip and die narrowband amplifiers operating at 1mW power*

S-parameters were measured at wafer level and used to design a narrowband 2.4GHz microstrip based amplifier. Amplifiers were fabricated on Rogers TMM-10 25 mil thick substrates. The measured gain against frequency characteristic is plotted in Fig. 2 for