



## Printed Microinductors for Flexible Substrates

**Magnetic composite layers are combined with hermetic coatings to optimize electrical and mechanical properties.**

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A method of fabricating planar, flexible microinductors that exhibit a relatively high quality factor ( $Q$ ) between 1 and 10 MHz has been devised. These inductors are targeted for use in flexible, low-profile power-converter circuits. They could also be incorporated into electronic circuits integrated into flexible structures, including flexible antenna and solar-sail structures that are deployable.

Fabrication of inductors on flexible, heat-sensitive substrates is typically limited by the need for high-temperature annealing step of the magnetic material. Highly loaded ceramic/polymer composite films can be seen printed and cured at lower temperatures, but suffer

poor adhesion. Thus, a new approach is required to enable the fabrication of high  $Q$  inductors (for power applications) on the flex substrates.

The microinductor comprises a planar spiral metal coil and a high-permeability magnetic thick-film (equivalent to the core of a conventional inductor) in the form of a ceramic/polymer composite. The metal spiral is fabricated by photolithography and etching of a copper-clad flexible polyamide substrate. The ceramic/polymer composite is deposited by stencil and screen printing, both above and below the metal spiral (see figure).

To obtain sufficient permeance and volume magnetization for the required degree of enhancement of inductance, the mass fraction of the ceramic in the ceramic/polymer composite must be about 95 percent, which is greater than the mass fractions of fillers typically incorporated into polymer-matrix thick films. In general, such a high mass fraction of filler can adversely affect printability and adhesion and can make the printed thick films susceptible to mechanical failure and

delamination during flexure. These adverse effects can be overcome, to a degree that makes it possible to produce an inductor of both acceptably high  $Q$  and acceptable mechanical properties, by (1) proper choice of the polymer resin and the ceramic magnetic powder filler for the thick-film formulation, in conjunction with (2) the use of a hermetic-coating technique.

Of the resins tested, polyester resins demonstrated the best loading and adhesion characteristics. A magnetic powder comprising Mn-Zn ferrite particles about 10  $\mu\text{m}$  in diameter was found to yield good magnetic properties. It was found that improved adhesion could be obtained through coating with vacuum-polymerized parylene.

*This work was done by Erik Brandon, Jay Whitacre, and Emily Wesseling of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

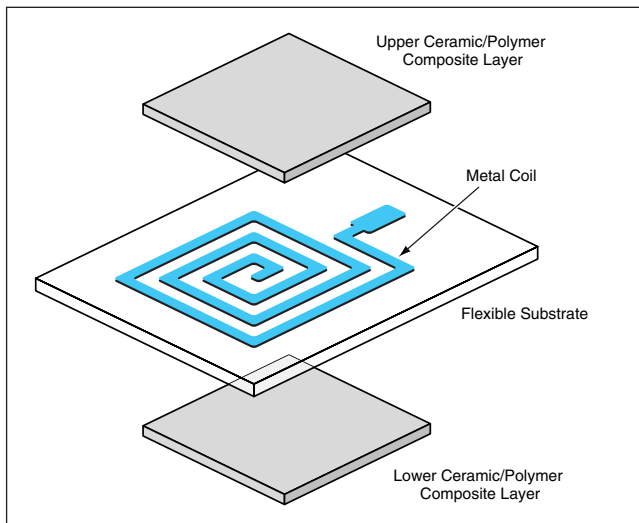
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A Flexible Inductor of Three Layers is fabricated as an integral unit by thick-film processing techniques.

## Series-Connected Buck Boost Regulators

**Sizes and power losses are smaller than those of conventional switching voltage regulators.**

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A series-connected buck boost regulator (SCBBR) is an electronic circuit that bucks a power-supply voltage to a lower regulated value or boosts it to a higher regulated value. The concept of the SCBBR is a generalization of the con-

cept of the SCBR, which was reported in "Series-Connected Boost Regulators" (LEW-15918), *NASA Tech Briefs*, Vol. 23, No. 7 (July 1997), page 42. Relative to prior DC-voltage-regulator concepts, the SCBBR concept can yield significant re-

ductions in weight and increases in power-conversion efficiency in many applications in which input/output voltage ratios are relatively small and isolation is not required, as solar-array regulation or battery charging with DC-bus regulation.

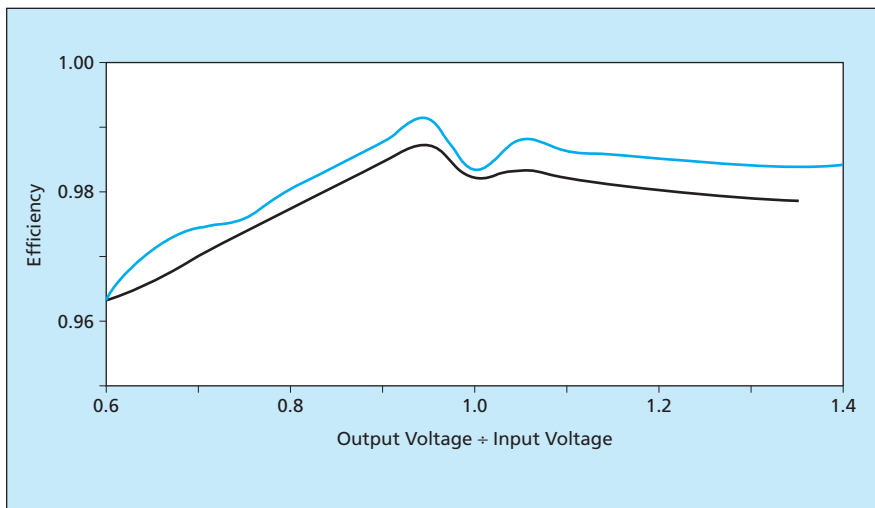


Figure 1. The Efficiency of a Breadboard SCBBR was measured as a function of output voltage with input voltage held at 120 V. (The upper curve is for a 5-A load; the lower is for a 2-A load.)

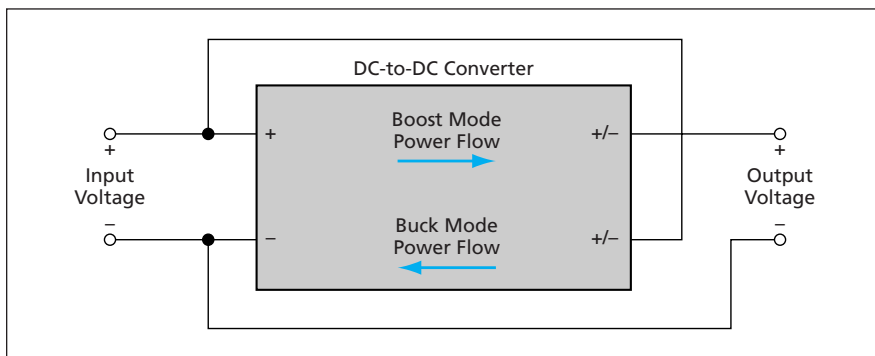


Figure 2. In a Basic SCBBR, the input side of a DC-to-DC converter is connected across the input power bus, while the output side is connected in series with the input power bus.

Usually, a DC voltage regulator is designed to include a DC-to-DC converter to reduce its power loss, size, and weight. Advances in components, increases in operating frequencies, and improved circuit topologies have led to continual increases in efficiency and/or decreases in the sizes and weights of DC voltage regulators. The primary source of inefficiency in the DC-to-DC converter portion of a voltage regulator is the conduction loss and, especially at high frequencies, the switching loss. Although improved components and topology can reduce the switching loss, the reduction is limited by the fact that the converter generally switches all the power being regulated.

Like the SCBR concept, the SCBBR concept involves a circuit configuration in which only a fraction of the power is switched, so that the switching loss is reduced by an amount that is largely independent of the specific components and circuit topology used. In an SCBBR, the amount of power switched by the DC-to-DC converter is only the amount needed to make up the difference between the

input and output bus voltage. The remaining majority of the power passes through the converter without being switched.

The weight and power loss of a DC-to-DC converter are determined primarily by the amount of power processed. In the SCBBR, the unswitched majority of the power is passed through with very little power loss, and little if any increase in the sizes of the converter components is needed to enable the components to handle the unswitched power. As a result, the power-conversion efficiency of the regulator can be very high, as shown in the example of Figure 1.

A basic SCBBR includes a DC-to-DC converter (see Figure 2). The switches and primary winding of a transformer in the converter is connected across the input bus, while the secondary winding and switches are connected in series with the output bus, so that the output voltage is the sum of the input voltage and the secondary voltage of the converter.

In the breadboard SCBBR, the input voltage applied to the primary winding is switched by use of metal oxide/semi-

conductor field-effect transistors (MOSFETs) in a full bridge circuit; the secondary winding is center-tapped, with two MOSFET switches and diode rectifiers connected in opposed series in each leg. The sets of opposed switches and rectifiers are what enable operation in either a boost or a buck mode. In the boost mode, input voltage and current, and the output voltage and current are all positive; that is, the secondary voltage is added to the input voltage and the net output voltage can be regulated at a value equal or greater than the input voltage. In the buck mode, input voltage is still positive and the current still flows in the same direction in the secondary, but the switches are controlled such that some power flows from the secondary to the primary. The voltage across the secondary and the current into the primary are reversed. The result is that the output voltage is lower than the input voltage, and some power is recirculated from the converter secondary back to the input.

Quantitatively, the advantage of an SCBBR is a direct function of the regulation range required. If, for example, a regulation range of  $\pm 20$  percent is required for a 500-W supply, then it suffices to design the DC-to-DC converter in the SCBBR for a power rating of only 100 W. The switching loss and size are much smaller than those of a conventional regulator that must be rated for switching of all 500 W. The reduction in size and the increase in efficiency are not directly proportional to switched-power ratio of 5:1 because the additional switches contribute some conduction loss and the input and output filters must be larger than those typically required for a 100-W converter. Nevertheless, the power loss and the size can be much smaller than those of a 500-W converter.

Because with slight additions the SCBBR can also function as a conventional buck-mode switching regulator, it can provide current-limited turn-on, protection against overcurrent, and bus switching. Finally, it should be noted that although the breadboard SCBBR design utilizes hard switching, resonant and soft-switching configurations should be viable as alternatives.

*This work was done by Arthur G. Birchenough of Glenn Research Center. Further information is contained in a TSP (see page 1).*

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