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The Anglet: A Novel Singlet Building-Block Subclass and Alternatives for E-plane Cross-Coupled Filter Design

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I. OVERVIEW

Standard-use technologies, for mid- to high-frequency range circuits, generally come in the form of microstrip and coplanar waveguides. Inherently, these types of circuits provide attractive attributes such as low cost, simple fabrication, and a high-degree of miniaturization and planarity. However, for high-performance and mission critical applications such as satellite constellations, broadcast communications, and remote sensing, these high-end circuits require a much more robust transmission line technology such as metallic waveguides which can accommodate higher operational frequencies and wider bandwidths with low signal loss and high-power handling.

In terms of filter design, resonators (or the resonant-modes) allow for selective frequencies to propagate throughout the circuit. A properly tuned set of resonators creates the collective passband of a filter. In conjunction, nonresonating-modes [1] can be viewed as modes that do not resonate within the vicinity of the selected passband and generally resonate far below or far above the passband. The advantage of the using nonresonating-modes lies in the ability to create additional (non-resonating) pathways throughout the circuit. These pathways create a functional bypassing method and allow for instances of destructive interference that will ultimately allow for the generation of transmission zeros in the filter response.

The nonresonating-mode concept [1] has allowed for many advanced topologies and high-performance filter designs to be put forth in the literature. A comprehensive discussion on the history and state-of-the-art of nonresonating modes provided in [2], allows for a dynamic view on the adoption of this technique and its ability to not only improve the characteristic filter response, but also facilitate highly compact and lightweight structures with low geometric complexity, ultimately paving the way for future generations of high-performance terrestrial and satellite communications. Furthermore, advancements in this technique, such as [3], have even demonstrated the inclusion of resonant irises into TM dual-

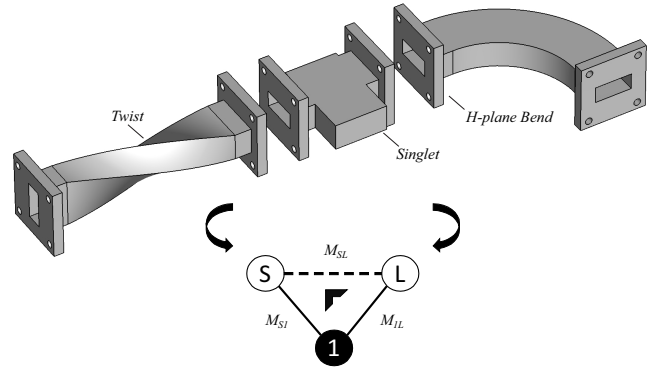


Fig. 1. Fundamental concept of the component integration and topology of the anglet. The resonating node is black and the source/load nodes are white. Solid lines indicate the direct-coupling paths, the dashed line indicates the bypass-coupling path, and the half-window frame symbol distinguishes the use of an anglet from a singlet in schematic form.

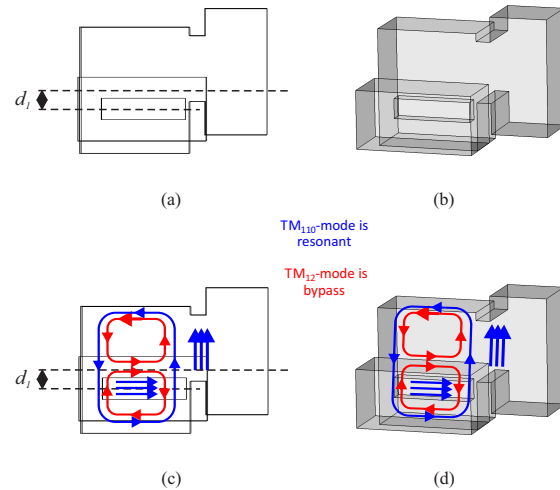


Fig. 2. A rectangular cavity anglet; front view (a) and perspective view (b), and the electromagnetic field orientation of the resonating and nonresonating modes; front view (c) and perspective view (d).

mode filters as a means of improving the nonresonating-mode technique described in [4].

In regards to fundamental first-order designs, singlets provide designers with an effective tool for generating one passband pole and one transmission zero though the use of a nonresonating-mode bypass coupling. This method allows for direct control of the transmission zero location and can influence the rejection characteristics above and below the

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TABLE I. Summary of basic rectangular waveguide cavities utilizing nonresonating modes.

Cavity Structure	Resonating Modes	Nonresonating Modes	Topology
Asymmetric Irises	TE ₁₀₁	TE ₂₀ (evanescent)	Singlet
E/H-plane Bend & Twist	TE ₁₀₁ /TM ₁₁₀	TE ₂₀ /TM ₁₂ (evanescent)	Anglet
Oversized H-plane	TE ₂₀₁	TE ₁₀	Singlet
TM Single Mode	TM ₁₁₀	TE ₁₀	Singlet
TM Dual Mode	TM ₁₂₀ & TM ₂₁₀	TM ₁₁	Doublet

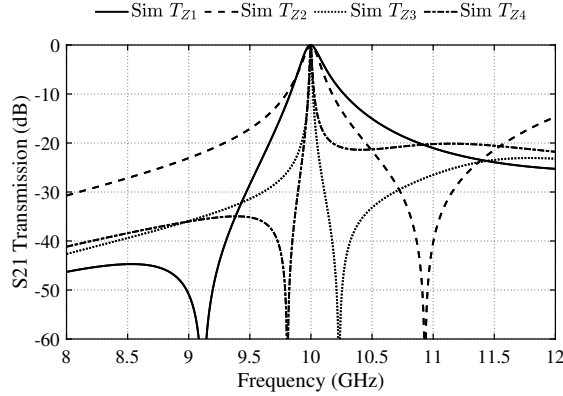


Fig. 3. The simulated transmission response of the rectangular cavity anglet described in Fig. 2. The transmission zeros (T_{Zi} for $i = 1, 2, 3, 4$) are varied by adjusting the port position via d_1 .

passband and has been applied to many advanced filter topologies, such as [5]–[9]. However, in regards to the use of asymmetric irises with use of evanescent modes as singlets [10]–[12], the generation of transmission zeros has been shown to be limited to the upper passband and located far away from the passband. This limitation seems to be caused by the relatively weak evanescent bypass coupling and has yet to be overcome in such designs. In light of the drawbacks of this type of structure, the authors have proposed an alternative approach and define a special case of the singlet which is able to not only create the necessary passband pole and functional transmission zero, but also integrate an E/H-plane bend and 90-degree polarization rotation into an ultra-compact structure. The introduction of this novel singlet building block has been defined and termed the *anglet* [13].

The following article is provided to the microwave community as an extended version of the award winning paper of the 2023 IEEE Radio & Wireless Week Student Paper Contest [13] and expands the concept in order to demonstrate novel topologies for advanced and compact filter design. Specifically, the use of multiple anglets are demonstrated as a unique alternative to typical E-plane cross-coupled filter designs, with and without the use of source/load coupling.

II. VERSATILITY

The ability to integrate multiple components (e.g., [14], [15]) into highly compact structures is an invaluable asset and has gained much attention in the literature due to the wide-spread use of additive manufacturing (e.g., [16]–[19]). However, despite these advancements in manufacturing, one of the most difficult challenges that filter designers face is finding

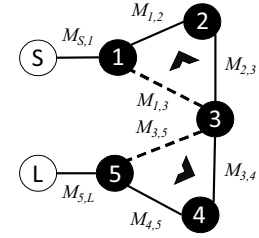


Fig. 4. Topology of the fifth-order filter utilizing two anglets without the use of source/load coupling. Resonating nodes are black and the source/load nodes are white. Solid lines indicate the direct-coupling paths and dashed lines indicate bypass-coupling paths.

suitable methods or structures that facilitate the generation of transmission zeros for improving the selectivity of the characteristic response, and understandably, this difficulty is further exacerbated – and in some cases making it infeasible – when attempting to manufacture these complex components with computer-numerical control (CNC) milling.

In light of these challenges, the versatile and unique physical profile of the anglet allows designers to overcome three fundamental challenges at once, that being: a 90-degree bend, a 90-degree polarization rotation, and the generation of a pole/transmission-zero pair. This structure is a first-order building block and as demonstrated in [13], can be readily applied in higher-order filter designs to achieve complex characteristics. Fig. 1 depicts the key concept of integrating three components, namely, a twist, bend, and singlet, into one fundamental unit. One of the key aspects of the anglet's versatility is due to the orthogonal positions of the input and output ports and is shown in the form of a rectangular cavity anglet in Fig. 2. Depending on the selection of either port, the resonating mode will be regarded as either a TE₁₀₁ or TM₁₁₀ mode, and the evanescent bypass coupling will in turn be regarded as either a TE₂₀ or TM₁₂ nonresonating mode, respectively, and in this manner, the selected orientation of the structure will either provide an E-or-H-plane bend and the inherent 90-degree polarization rotation. This unique physical profile distinguishes the anglet from other nonresonating-mode designs as highlighted in Table 1.

III. FUNDAMENTALS

As described in [13] and Fig. 1, the topology diagram of the anglet includes a half-window symbol in order to communicate the angular (E-plane or H-plane) change and intrinsic polarization rotation. Fig. 2(a) and (b) depict the rectangular cavity anglet with the input port orientated towards the front, and the resulting bend and twist motion ending in the H-plane direction. Fig. 2(c) and (d) are provided as a depiction

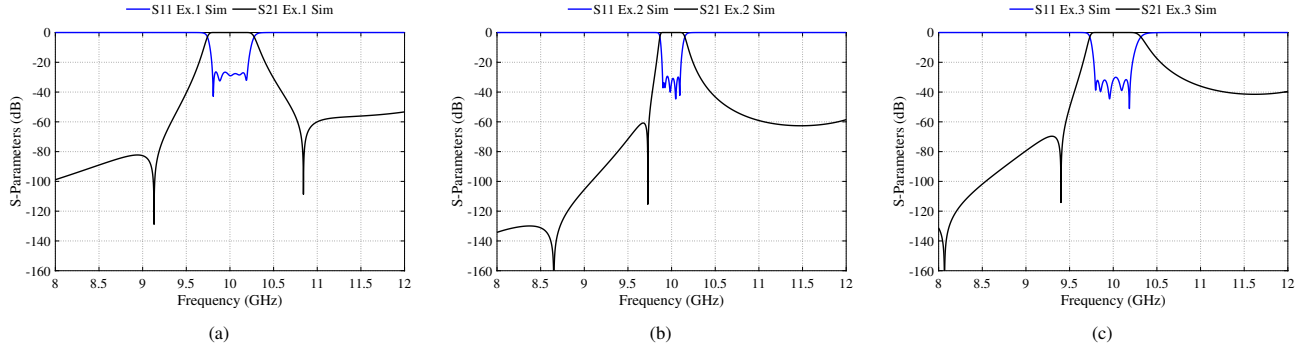


Fig. 5. Lossless simulated S-parameter results of three sample variations of a fifth-order filter utilizing two anglets without the use of source/load coupling as proposed in Fig. 4. (a) 4.0% FBW, (b) 2.1% FBW, and (c) 4.1% FBW.

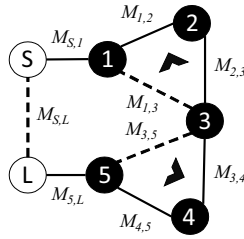


Fig. 6. Topology of the fifth-order filter utilizing two anglets and source/load coupling. Resonating nodes are black and the source/load nodes are white. Solid lines indicate the direct-coupling paths and dashed lines indicate bypass-coupling paths.

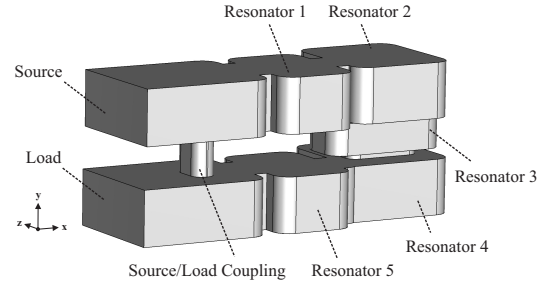


Fig. 7. Vacuum shell of the proposed 4.0% FBW filter utilizing two anglets with source/load coupling; the structure is formed from three regular rectangular cavities and two rectangular-shaped anglets as the interconnects.

of the resonant and nonresonant mode's orientation throughout the structure.

The characteristic response of an anglet can be described by a 3×3 coupling matrix using equations (1) through (3), from [7], [13], [20], [21] as:

$$[m] = \begin{bmatrix} 0 & M_{S1} & M_{SL} \\ M_{S1} & M_{11} & M_{1L} \\ M_{SL} & M_{1L} & 0 \end{bmatrix}, \quad (1)$$

$$Q_{e_{sii}} = \frac{\pi \cdot f_{\tau_{sii}} \cdot \tau_{sii}(f_{\tau_{sii}})}{2}, \quad (2)$$

$$M_{SL} = \frac{M_{S1}M_{1L}}{\Omega_Z}, \quad (3)$$

where τ_{sii} is the group delay, $f_{\tau_{sii}}$ is its associated center frequency for $i = 1, 2$, and the authors propose (3) as a solution to the source/load coupling, where Ω_Z is the normalized transmission-zero frequency. A demonstration on the control of the transmission zero location is given in Fig. 3. Four test cases are provided where the transmission zero is moved above and below the 10 GHz center-frequency location.

IV. MULTI-ANGLET FILTER DESIGN

An anglet-based filter was described in [13] as a quasi-triplet design where the transmission zero was placed below the passband using two rectangular cavities and one L-shaped anglet cavity. This initial study demonstrated that 1) the transmission zero can be placed in the lower passband and

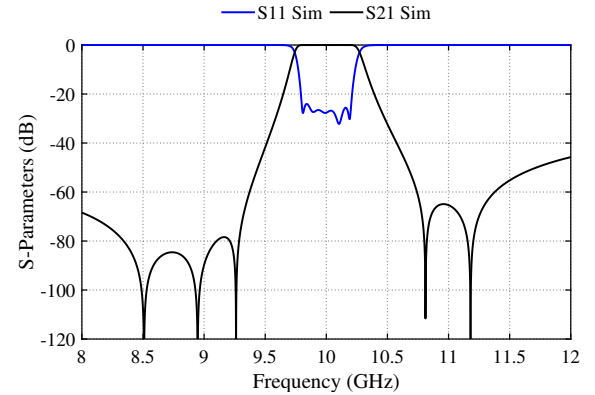


Fig. 8. Lossless simulated S-parameter results of the fifth-order, 4.0% FBW filter utilizing two anglets with source/load coupling as proposed in Fig. 6 and modelled in Fig. 7.

2) the transmission zero location can be placed close to or far away from the passband. This demonstration is contrary to previous evanescent-mode designs that utilized asymmetric irises [10]–[12]. In order to demonstrate the use of anglets in higher-order designs, as well as illustrate the advanced use of the transmission zeros, we demonstrate three different multi-anglet filter designs with various characteristic responses and fractional bandwidths (FBW) by simulation. In this manner, strong region characteristics can be demonstrated at different locations in the frequency band. The proposed topology is given in Fig. 4 and demonstrates the use of two anglets to

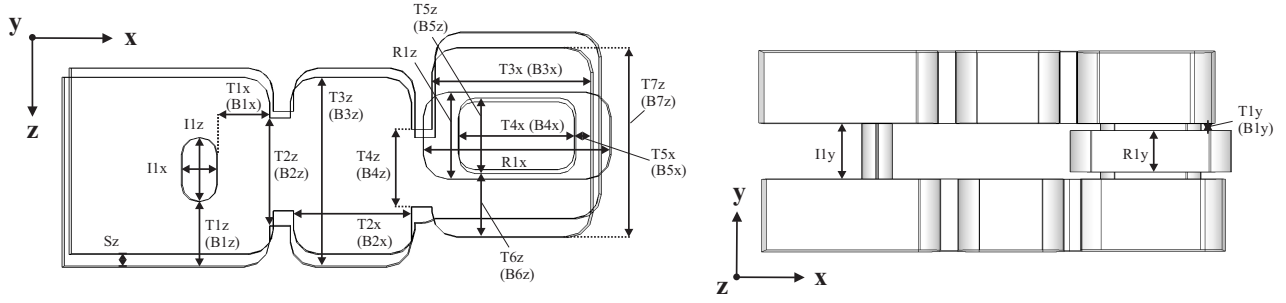


Fig. 9. Dimensional layout of the fabricated filter utilizing two anglets with source/load coupling. To simplify the drawings, the structure is dimensioned with regards to the top filter section with the label abbreviation (T) and its synonymous dimension in the bottom filter section is of dimension (B). I is the source/load iris, R is the middle resonator cavity, and S is an offset. Input/output waveguides are standard WR90. See Table II for dimensional values.

create a fifth-order filter with two transmission zeros. This can be realized with use of three resonator cavities and two rectangular anglet cavities. Furthermore, it can be noted that the use of two anglets in this manner allows for the combination of two 90-degree polarization rotations (i.e., 0 or 180 degree rotation), ultimately resulting in the output port of the filter having the same polarization orientation as the input port (i.e., the twist is effectively eliminated). Three different examples of simulated S-parameters of this fifth-order concept are shown in Fig. 5(a-c) for operation at 10 GHz with fractional bandwidths of approximately 4.0%, 2.1%, and 4.1%, respectively. The transmission zeros that are portrayed are located in different positions and demonstrate strong rejection characteristics in the selected regions. For instance, in Fig. 5(b), the transmission zero closest to the passband reaches ≈ 60 dB at 9.68 GHz while the transmission zero furthest from the passband reaches ≈ 130 dB at 8.4 GHz.

V. MULTI-ANGLET FILTER DESIGN WITH SOURCE/LOAD COUPLING

Further advancements on the multi-anglet filter designs that are proposed in the previous section can include the canonical effects provided by the use of source/load coupling. In this manner, a fifth-order filter response can take advantage of five transmission zeros. The proposed topology is given in Fig. 6 while the vacuum shell of the filter model is given in Fig. 7 where the source/load coupling can be seen clearly as a thick iris. The simulated S-parameters of this design are shown in Fig. 8 for operation at 10 GHz with 4.0% FBW. Three transmission zeros are placed below the passband and two transmission zeros are placed above the passband. Reviewing the model provided in Fig. 7, it can be noted that this design is suitable for either additive or subtractive manufacturing, does not require any overly complex geometries, and can act as an alternative approach to classical [22] E-plane folded and cross-coupled designs.

VI. PROTOTYPING

In order to verify the proposed design methodology, the canonical design from Fig. 6 and Fig. 7 is manufactured for X-band operation in aluminum alloy. The basic dimensions are provided in Fig. 9 and Table II. The filter is milled with two main sections that house the four (upper and lower) resonator

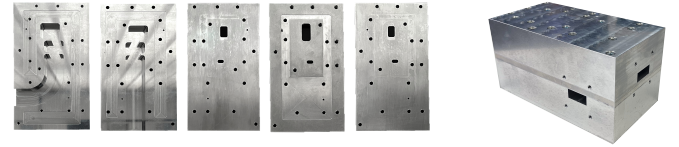


Fig. 10. Fabricated X-band prototype of the fifth-order filter utilizing two anglets with source/load coupling from Fig. 7 and Fig. 9. The internal filter cavities and iris-coupling foils are shown disassembled, and the fully assembled filter is shown on the right.

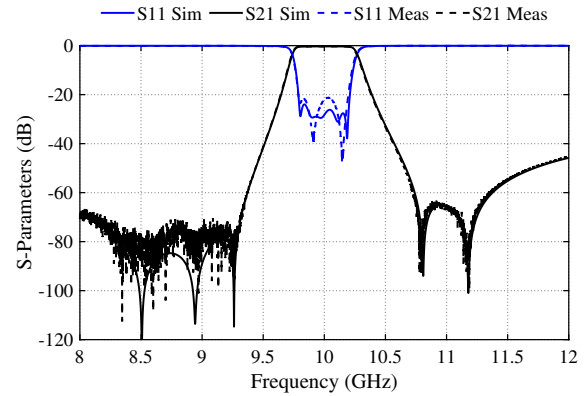


Fig. 11. Simulated versus measured S-parameter results of the fifth-order, 4.0% FBW filter with source/load coupling. Effective conductivity is taken as 5.6 MS/m.

cavities and input/output transitions, while three thinner sections are designed for the fifth resonator and the corresponding transition irises. Fig. 10 depicts each of the milled components and the fully assembled filter. Once assembled, the filter was tested using a Rohde & Schwarz ZVA67 network analyzer. Fig. 11 presents a comparison of the simulated and measured results over 8.0 GHz to 12.0 GHz. This direct comparison demonstrates very accurate measured results; the measured return loss is better than 20.0 dB throughout the passband and the measured insertion loss is in the range of 0.31 dB to 0.46 dB. A close-up view of the passband insertion loss is given in Fig. 12 over the range of 9.5 GHz to 10.5 GHz. Analyzing the filter's response, the unloaded quality factor is estimated to be approximately $Q_u \approx 2400$. In addition to the results discussed, the simulated versus measured group delay response is provided in Fig. 13 and exhibits a very accurate

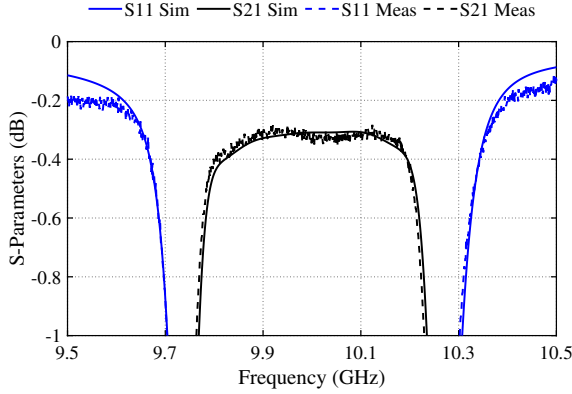


Fig. 12. Close up view of the simulated versus measured insertion loss of the fifth-order, 4.0% FBW filter with source/load coupling. Effective conductivity is taken as 5.6 MS/m.

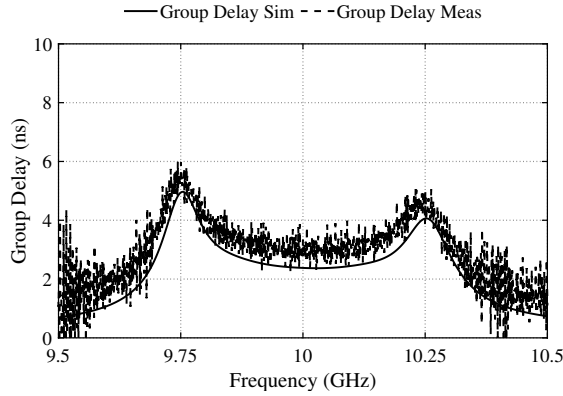


Fig. 13. Simulated versus measured group delay response of the fifth-order, 4.0% FBW filter utilizing two anglets with source/load coupling. Effective conductivity is taken as 5.6 MS/m.

measured profile compared to the simulation.

VII. CONCLUSION

This article has provided an extended view of the anglet concept. Novel filters have been proposed by utilizing multiple anglets for demonstration of various filter characteristics with multiple transmission zeros. The versatility and control over the anglet's transmission zeros allow for an alternative approach to typical E-plane folded designs and ultimately provide engineers with a new first-order building block for filter design. A design utilizing two anglets to create an E-plane folded structure with source/load coupling is selected for fabrication and demonstration of a canonical response with five passband poles and five transmission zeros. Highly accurate measurements are achieved frequency band of interest. As exemplified in this work, RF filter designers can readily apply this new building-block concept to achieve higher-order designs and complex filter characteristics.

VIII. ACKNOWLEDGEMENT

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TABLE II. Filter dimensions.

Dimension	Value (mm)	Dimension	Value (mm)
T1x	6.490	B1x	6.800
T2x	14.670	B2x	14.946
T3x	19.360	B3x	20.312
T4x	14.244	B4x	14.244
T5x	1.777	B5x	3.315
T1y	1.000	B1y	1.000
T1z	7.796	B1z	6.565
T2z	13.038	B2z	12.200
T3z	22.860	B3z	22.860
T4z	9.348	B4z	10.480
T5z	9.200	B5z	8.286
T6z	7.622	B6z	6.037
T7z	22.860	B7z	22.860
I1x	4.300	I1z	7.750
I1y	7.873	R1y	5.873
R1x	22.860	R1z	10.602
Sz	1.231		

For schematization, T signifies the top structural dimensions, while B signifies the synonymous bottom dimensions. I is the source/load iris, R is the middle resonator cavity, and S is an offset.

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